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THE SILVER MINE OF COLQUIJIRCA, PERU.

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Introduction.—The Colquijirca mine, which at times has been the most productive silver mine of North and South America, is situated 8 kilometers south of Cerro de Pasco in the foothills of the Junin pampa, at an elevation of about 4,000 meters. It is a small mine; the greatest depth attained, as far as I know, is about 700 feet. The folded ore beds are said to extend for about 2,000 feet along the strike. Figure 1 shows the workings and the several ore beds. Worked with unsatisfactory results at the outcrops in Colonial times, it was long abandoned until opened by A. Rizo-Patron about 1910 by a tunnel from the level of the pampa. The work was continued later by the present owner, Mr. E. E. Fernandini. The ore proved remarkably rich. I am informed by Professor W. S. Hutchinson of the Massachusetts Institute of Technology that the production from 1911 to 1919 inclusive amounted to nearly 13,000,000 ounces of silver with some lead and copper. Dr. Ahlfeld states that in the two years 1927 and 1928, the silver production aggregated 12,000,000 ounces. The total silver production has not been made public, but is probably not less than 40 million ounces. For comparison, it may be recalled that the Premier mine, British Columbia, produced 27,000,000 ounces of silver from 1918 to 1930 inclusive. The Tintic Standard Mine produced 4,000,000 ounces in 1925. The whole silver production of the Tintic district from 1869 to 1929 inclusive is estimated at 217,000,000 ounces. The Cobalt district, Ontario, from 1903 to 1930 yielded 365,000,000 ounces.

Potosi, Bolivia, is believed to have yielded 960,000,000 ounces since 1545 A.D.

The Colquijirca ores are rich; first class ore averaging 60 ounces per ton, second class, 40 ounces, and poor ores, 20 ounces or less. The poor ores contain about 15 per cent lead. For various reasons the production has declined materially since 1930.

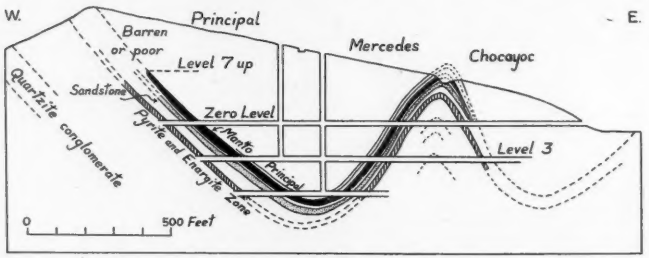

FIG. 1. Vertical E.–W. section across the Colquijirca mine. After F. Ahlfeld.

I believe all the ores are now smelted by the Cerro de Pasco Company.

Some of the ores have been described by various authors.[1] Dr. Ahlfeld's excellent article contains a description of the geological features as well as a description of the ores. I have borrowed from him the data on the general geology of the mine.

In 1927, I received a fine suite of specimens from the mine for the purpose of a report. From this report I have selected certain phases relating to the mineralogy and analyses, which did not seem to be of special economic interest. I owe several analyses to the well known skill of Mr. E. V. Shannon, and three photographs of ores to the kindness of Prof. W. H. Newhouse.

On the west, in the footwall, lie sandy shales and sandstones

[1] Orcel, J., et Rivera Plaza, Gil: Étude microscopique de quelques minerais métalliques du Perou. Bull. Soc. Française de Min., 52, 91–107, 1920. McKinstry, H. E.: Interpretation of Concentric Textures at Colquijirca, Peru. Amer. Miner., 14, 430–433, 1929. Lindgren, W.: Pseudo-eutectic Textures. ECON. GEOL., 25, 1–13, 1930. Ahlfeld, F.: Die Silberlagerstätte Colquijirca, Peru. Zeit. prakt. Geol., 40, 81–87, 1932.

believed to be of Carboniferous Age. These are unconformably covered by a series of limy and argillaceous strata 200 meters thick, beginning with a quartzite conglomerate. This whole series is markedly folded and held to be of late Triassic age. Jurassic limestone forms the hills on the east side and covers these beds conformably. Two smaller intrusive masses of dacite porphyry lie to the south and west of the mine.

The mineralized part of the series has a thickness of from 30 to 50 meters. Three or four beds (mantos) are mineralized and separated by sandstone or sandy shale. In places the several mantos merge, yielding an ore zone which may be 12 meters thick. The upper manto, reaching 5 meters in thickness, contains the rich silver-copper ores. Underneath this is the lead manto, which appears on the west side and as well in the Chocayoc part of the field. Underneath this, but separated from it by a sandstone layer, is the lowest manto of pyritic copper ore with enargite, not everywhere fully mineralized.

The relations of these different "mantos" or mineralized beds have naturally an important bearing on the genesis, but lack of acquaintance with the details of ore occurrence prevents me from entering on this subject. Undoubtedly they indicate considerable variations in the temperature of deposition. The influence of the country rock is also important and it is believed that the more calcareous beds (as in Chocayoc) favor the deposition of galena and pyrite and a less marked silver mineralization.

The silver appears in force with the barite-tennantite-stromeyerite mineralization. The enargite comes in chiefly in the pyritic manto. Speaking generally, the deposit is distinctly epithermal and was formed at temperatures which, never high, declined markedly towards the end of the epoch. High-temperature minerals are absent.

The Country Rock and Its Alteration.—The most common country rock in the mantos is a gray, brown, or black chert consisting of fine-grained chalcedonic quartz, the individual grains showing fibrous extinction. Fibers showing cell structure are abundant, indicating silicified wood. These rocks are calcareous

shales replaced by silica by colloidal processes. Occasionally unaltered clay shales with small clastic quartz grains are noted. The cherts commonly contain specks of pyrite or chalcopyrite. Later veinlets of lighter chalcedony intersect the chert. Unaltered gray or brown limestone occurs in the Chocayoc section, commonly containing a little pyrite, sphalerite, and galena, as well as veinlets of ankerite or calcite. The contracting and easily fractured gel, hardening to chert, offered excellent paths for the mineralization and is infilled with barite and sulphides or replaced by these minerals. In places the chert contains areas or veinlets of coarser quartz.

As some of the shales were rich in alumina, kaolin resulted during this silicification. The kaolin forms minor white or greenish soft masses. Some is amorphous pholerite. Other specimens from Mercedes show a crystalline kaolinite with $n = 1.565$. Small pyrite grains replace the kaolinite. Chalcedony, quartz and kaolin were the result of the first attack of the hot mineralizing water on the rocks. They were practically formed before any of the following phases of mineralization, though a little chalcedony, kaolin, and calcite may have accompanied the deposition of the ore minerals.

Other Gangue Minerals.—Barite is almost the only important later gangue mineral. Some of the barite plates formed in open spaces attain a length and width of 5 or 6 centimeters and a thickness of 5 to 7 millimeters. Barite is replaced by any of the sulphide minerals, but never replaces them. A little calcite, or ankerite, is in places deposited on galena. The limestone from Chocayoc is partly replaced by dolomitic and ankeritic carbonates. A specimen from the lower manto of the Mercedes shows ankerite or siderite with later galena and still later coatings of kaolin.

Pyrite.—Pyrite in minute crystals is common in the chert and other country rocks. Massive pyrite occurs generally with the lead ores; in places, it assumes a colloform habit. This pyrite, as well as the marcasite, appears to contain very little or no silver.

Marcasite.—In some Chocayoc ores large spear-shaped crystals of marcasite replace the pyrite. Most abundant is marcasite

in the very late marcasite-specularite mineralization, occurring here as excellent small crystals on the sphalerite.

Sphalerite is present in varying quantities, being most abundant in the lead ores. It is generally of light color and may form druses covered by dolomite or halloysite. Some of the late sphalerite is of dark color and beautifully colloform; it contains no silver and no bismuth.

Galena.—The galena of the "manto de plomo" and Chocayoc is massive and granular; sometimes in crystals of octahedron and cube. When pure it appears to contain from 14 to 26 ounces of silver, which is present in small grains of argentite and tennantite, probably also in solid solution. The galena always follows the sphalerite and may replace it along the cleavage, giving rise to dendritic texture. Where chalcopyrite is present in the lead ores it is always later, replacing galena along its periphery. As little galena is present in the rich silver ores, its paragenetic position is not so easily determined here.

Enargite.—This mineral is sparingly present as crystalline masses in the pyritic manto; it replaces pyrite and barite and is replaced by all later sulphides. Luzonite, said to be older than enargite, was identified by Ahlfeld.

Tetrahedrite.—The presence of tetrahedrite is suspected in one or two specimens, but on the whole the ores are remarkably poor in antimony.

Tennantite.—Tennantite is one of the most abundant minerals of the older series; it replaces chert, barite, pyrite and sphalerite. It is black and has a dark reddish brown streak; greenish gray in polished section; generally massive, but also in small, sharp tetrahedrons. It apparently always contains silver, but in varying amounts; zinc is also variable, some samples containing practically none, others up to 12 per cent. Bismuth, when present, always indicates replacing bismuth minerals.

Specimen 60, which is simply labelled "filling of ore in brecciated silica" is a breccia of brown chert containing a little pyrite in minute grains; it is cemented by barite plates between which is abundant black tennantite in minute tetrahedrons. For analysis

the chert was separated by heavy liquid and the residue, containing only barite and the sulphide mineral, was analyzed. There are no other sulphides present. After deducting 39.1 per cent barite, the following result was obtained.

ANALYSIS No. 60.—COLQUIJIRCA, PERU.

E. V. Shannon, Analyst.

		Ratio
Copper	34.87	0.549
Silver	4.27	0.039
Lead	.23	0.001
Zinc	12.07	0.185
Iron	1.15	0.020
Bismuth	none	
Arsenic	20.60	0.275
Antimony	trace	
Sulphur	26.64	0.833
	99.83	

The presence of large amounts of zinc and silver is noteworthy. There seems to be no escape from the conclusion that these metals are integral parts of the tennantite. Also noteworthy is the absence of bismuth, showing that the tennantite and silver mineralization was not normally accompanied by a bismuth mineralization. This gives:

Cu (Zn, Pb, Fe, Ag)	0.794	or approximately		$6 \times 135 = 810$
As	0.275	"	"	$2 \times 135 = 270$
S	0.833	"	"	$6 \times 135 = 810$

which leads to the Prior and Spencer formula of $Cu_6 As_2 S_6$.

Specimen 62, from Mercedes, shows barite plates on and in brown chert. In and between barite is tennantite with later chalcopyrite. Tennantite occurs in part as small tetrahedrons. In polished section some areas are uniform, others contain much chalcopyrite. With the tennantite occur the following later minerals:

1. Bluish gray stromeyerite.
2. A soft greenish gray mineral in pseudo-eutectic intergrowth

with tennantite, or as veins in it. Slightly attacked by HNO_3, fumes do not tarnish; KCN attacks slightly, rubs clean; may possibly be emplectite.

3. Light gray soft aggregates in tennantite, browned by HNO_3, quickly blackened by KCN; darkens with $FeCl_3$; in places intimately intergrown with tennantite in feathery aggregates. These three later minerals evidently contain bismuth. A part of the section, containing only tennantite, chalcopyrite and mineral No. 2, was analyzed:

ANALYSIS NO. 62.—COLQUIJIRCA, PERU.

E. V. Shannon, Analyst.

		Recalculated	Ratio
Barite	26.16		
Silver	4.08	5.56	0.052
Copper	29.68	40.44	0.636
Lead	0.90	1.22	0.006
Iron	1.52	2.07	0.037
Zinc	0.06	0.09	0.001
Arsenic	10.82	14.74	0.197
Antimony	0.12	0.16	0.001
Bismuth	8.20	11.17	0.054
Sulphur	18.02	24.55	0.765
	99.56	100.00	

An attempt was made to calculate this analysis on the assumption that emplecite ($Cu_2Bi_2S_4$) is present.

	Bi	Pb	Zn	Cu	Fe	S
Galena		0.006				0.006
Chalcopyrite				0.037	0.037	0.074
Sphalerite			0.001			0.001
Emplectite	0.054			0.054		0.108
				0.091		0.189

There remains after these amounts are subtracted:

Cu (Ag)	0.597
As (Sb)	0.198
S	0.576

which corresponds very well with the Prior and Spencer formula $Cu_6As_2S_6$. It is, therefore, reasonably certain that mineral No. 2 is emplectite and that the principal mineral is tennantite.

Galena.—Galena is not common in the rich upper mantos of Principal and Mercedes, but appears rather abundantly in the underlying " manto de plomo " and in Chocayoc. It has a normal granular texture but in places appears in crystals of combined cube and octahedron. It is not rich in silver, assays giving from 8 to 26 ounces per ton; much of this probably comes from small inclusions of tennantite and argentite. Most of the ores contain a trace of gold. The galena always follows the sphalerite and replaces it abundantly, commonly along the cleavages, giving rise to dendritic texture.

Chalcopyrite.—The main part of the subordinate chalcopyrite is associated with tennantite and replaces it. Rounded replacement remnants of pyrite occur in it; chalcopyrite may rim and surround tennantite; there is a very little bornite, formed by replacement or unmixing. There is also a later chalcopyrite appearing with the marcasite-specularite mineralization.

Wittichenite (Cu_3BiS_3).—Some of the ores are rich in bismuth. The principal bismuth mineral is the rare mineral wittichenite. This was first found in the lower manto of the Mercedes. As far as I know, it is the first definite identification of the mineral from the Americas. The bismuth minerals apparently always replace tennantite, but bismuth also appears, probably in chemical combination, in the stromeyerite.

Specimen No. 24 shows black chalcedonic chert (with some wood fibers) covered by replacing barite; the sulphides mostly fill spaces between barite plates. The fine-grained chalcedony is shattered and infilled by lighter veins of the same substance. The wittichenite occurs in steel-gray massive aggregates, tarnishing markedly pale brown on the surface. Streak black; mild or slightly brittle; contains residuals of pyrite, also a little chalcopyrite. The reactions are as follows: HNO_3 browns rapidly, rubs blue or brown, fumes tarnish brown; attacked longer, turns almost black. HCl negative, acid turns yellowish. KCN etches

irregularly blue or brownish. With $HgCl_2$, $FeCl_3$ and KOH, faintly brown.

The mineral was carefully hand-picked but the sample still contained some barite and pyrite and a very small amount of chalcopyrite, less than one per cent.

ANALYSIS NO. 24.—COLQUIJIRCA, PERU.

E. V. Shannon, Analyst.

Insoluble	Per cent.	Ratio	Recalculated
Barite and chert	9.12		
Silver	0.01		0.01
Copper	30.56	0.481	38.20
Iron	5.10	0.091	
Lead	.68	0.003	0.85
Zinc	trace		
Arsenic	0.24	0.003	0.30
Antimony	0.20	0.003	0.25
Bismuth	33.40	0.160	41.75
Sulphur	20.88	0.651	18.85
	100.19		100.21

Ni and Co are absent. If the impurities of 9.12 per cent gangue and 5.1 Fe + 5.8 S = 10.9 pyrite be subtracted, the analysis may be recalculated as shown in the last column. Wittichenite requires 38.4 copper, 42.1 bismuth and 19.50 sulphur. The correspondence is very close. The ratios give the correct formula $3Cu_2S.Bi_2S_3$: Bi(As, Sb) 0.166; Cu(Pb) 0.484; S 0.469. Ahlfeld also reports the presence of klaprothite in intimate intergrowth with wittichenite.

Other Silver Minerals.—Argentite occurs sparingly. In my specimens I found no other minerals of this class except stromeyerite and native silver. Orcel reports proustite, and Ahlfeld found sternbergite and pearcite, the latter replacing stromeyerite and sternbergite.

Stromeyerite.—Stromeyerite is the most valuable silver sulphide at Colquijirca; I consider it to be of hypogene origin (in agreement with Ahlfeld). It replaces tennantite and chalcopyrite, rims them or forms pseudo-eutectic intergrowths, particu-

larly with the tennantite. A specimen from the lower manto in the Mercedes shows pyrite, tennantite, chalcopyrite and stromeyerite in brown chert, also a little galena but no sphalerite. Native silver appears in some sections. In part the minerals form separate masses. Enough of the pure stromeyerite was isolated for analysis.

ANALYSIS NO. 16.—COLQUIJIRCA, PERU.

E. V. Shannon, Analyst.

		Recalculated	Recalculated to pure material	Ratio
Insoluble	2.39	2.39		
Chalcopyrite		1.48		
Silver	45.58	45.58	47.16	0.437
Copper	32.37	31.87	32.97	0.519
Iron	.48			
Bismuth	2.12	2.12	2.19	0.015
Arsenic	trace	trace	trace	
Antimony	trace	trace	trace	
Zinc	trace	trace	trace	
Lead	.46	.46	.47	0.0023
Sulphur	17.11	16.61	17.21	0.538
	100.51	100.51	100.00	

The material analyzed contained a little chalcopyrite (separated in the above analysis) and possibly the lead is present as galena. The place occupied by the bismuth is doubtful. No definite bismuth minerals were observed.

As shown by the ratios, the material is almost pure massive stromeyerite, in which, however, appears to be a little admixed chalcocite, shown as small bluish areas in polished section. It therefore contains a little less silver than required by the usual formula, $Ag_2S.Cu_2S$. The color of stromeyerite is bluish-purplish gray. It is strongly anisotropic. The mineral can no longer be considered rare, as it has lately been identified from many deposits in North and South America.

McKinstry appears to have shown that some of the stromeyerite is earlier than galena, sphalerite and chalcopyrite, but I believe this means that the latter three minerals in the specimens

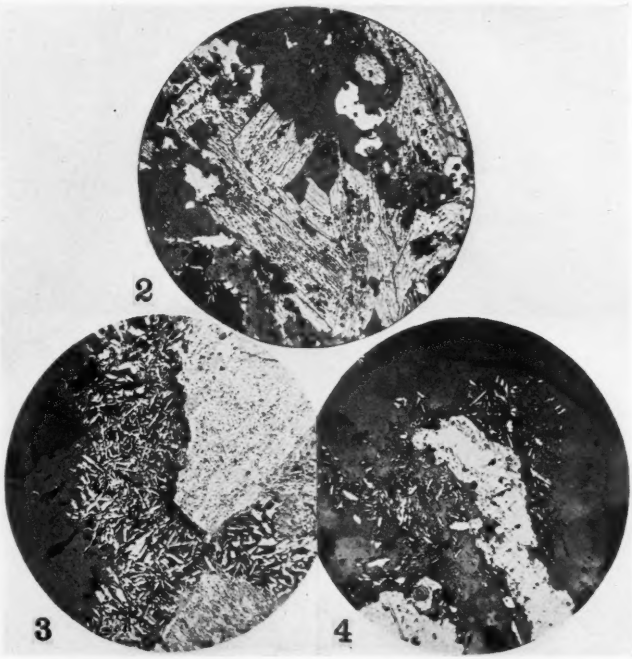

FIG. 2. Photograph of polished section. Late marcasite mineralization. Black; chalcedony. Gray, older sphalerite. White, galena. Strands and sheaves of marcasite replacing older sphalerite. × 55.

FIG. 3. Photograph of polished section, showing late specularite-marcasite mineralization. Light gray, sphalerite replaced by marcasite; dark gray, chalcedony. Crystal aggregate specularite. × 38.

FIG. 4. Photograph of polished section. Late sphalerite mineralization. Dark gray, chalcedony; light gray elongated areas, older sphalerite surrounded and partly replaced by specularite in small crystals. × 36.

studied by him belong to the latest phase of ascending mineralization described below. Stromeyerite appears to be most abundant in the upper tennantite manto of Principal and Mercedes. Chalcocite is not abundant in the rich ore. Ahlfeld states that chalcocite occurs in the pyritic manto which carries enargite; chal-

cocite replaces the latter and is said by Ahlfeld to be of hypogene origin.

The Late Specularite-Marcasite Phase.—A very late phase of probably hypogene mineralization is recognized by the presence of specularite in well developed though small crystals of steep rhombohedrons. "Hematite" is said to be widespread in the mine, though not in large masses, but occurring in various "mantos" so that it is not confined to any particular older min-

FIG. 5. Drawing of contact on Fig. 4 between sphalerite (S) and chalcedony (C) showing crystals of specularite (black) replacing older sphalerite and chalcedony. × 150. (Drawn by W. H. Newhouse.)

eralization. Specimens were noted from the pyritic manto, Principal, and from a lower manto with galena in Mercedes. It was first observed that veinlets of chalcedony contained small crystals of specularite. The accompanying minerals were later found to be marcasite in delicate, sometimes curved strands, uniting in sheaves and larger prismatic aggregates; further, chalcopyrite and galena occur in veinlets through the marcasite. This association occurs in solution cavities in the older sphalerite, later filled with chalcedony. Specularite forms on the walls (Fig. 3), and the marcasite spreads by replacement in the older sphalerite (Fig. 4), and probably also in the older galena. Crystallized marcasite was observed on some of the older sphalerite. This mineralization contains no recognizable silver minerals nor any bismuth

minerals. It was at first considered supergene, but I now hold that it is the latest hypogene phase. The presence of marcasite indicates a low temperature. If this phase resulted from descending water, it is difficult to understand why it should not be rich in silver.

It is known of course that hematite and even crystallized specularite may develop in oxidized ores and in laterite, but its presence in the later hypogene phases of epithermal deposits is certainly very unusual. Burbank[2] mentions it as forming part of the earliest mineralization at Bonanza, Colorado. Here it occurs in silicified volcanic rocks with pyrite and kaolin; the presence of marcasite is not mentioned. Specularite is found in places in mesothermal deposits; its occurrence in early phases of the Camp-Bird mine, Colorado, is believed to be associated with Eocene intrusives, on the supposition that the vein represents an epithermal phase superimposed on a mesothermal mineralization. It is not believed that we have full information as to the stability field of specularite.

Supergene Native Silver.—If Dr. Ahlfeld and myself are correct in holding the stromeyerite hypogene, the supergene minerals are narrowed down to native silver (probably also some chalcocite and pearceite). Silver is very abundant in the upper mantos of Principal and Mercedes and results chiefly from the breaking down of stromeyerite. It occurs as veinlets, masses and knobs in stromeyerite, as illustrated in my paper on pseudo-eutectic intergrowths; or it forms sheets replacing tennantite-stromeyerite veinlets, or as wires and hooks in other ores. Rarely it appears in the lead ores. Naturally some of these ores contain several thousand ounces per ton.

The zone of oxidation appears to be poor and shallow; Ahlfeld states the depth as 50 meters. On the other hand the zone of native silver is deep and extensive, although principally confined to the upper tennantite-stromeyerite manto in Principal and Mercedes.

General Genetic Consideration.—According to Ahlfeld, the

[2] U. S. Geological Survey, Prof. Paper 169, 1932, p. 68 and Pl. IX.

history began by silicification, dolomitization and kaolinization of the country rock followed by deposition of barite and later pyrite, poor in silver. Then followed the enargite-pyrite ore of the lowest manto, and finally the latest silver-rich tennantite, stromeyerite and the lead ores. He interprets the differences of mineralization as "primary depth zones." Looking at the section, it seems that all the variations in the hypogene are confined within a stratigraphic thickness of 30 to 50 meters, and that it would be difficult to assume that the vertical depth can have had any great influence. I am willing to admit Ahlfeld's general succession and that the pyritic manto was probably the oldest development at a fairly high temperature, but incline to ascribe the differences largely to a change of composition of the solution. The influence of country rock seems to be limited to the preferential development of lead in the lime-rich sections.

The distribution of the silver is of interest: There is little or no silver in the early pyrite; little, comparatively speaking, in the pyrite-enargite ore and in the lead ore; an abundance of silver in the tennantite manto; finally no silver minerals in the latest specularite-sphalerite marcasite mineralization. There is further to be considered the sudden appearance of bismuth in spots in the tennantite ore and its absence in the latest phase just referred to; I believe that much of these sudden changes of mineralization are caused by changes in the composition of the solutions. There is finally the question of ducts. It seems probable that the dacite porphyry appearing on the surface less than a mile to the south is genetically related to the ore, and it also seems probable that by proper development such ducts or feeders might be discovered by which the mineralizing solutions reached the beds which were to constitute the main loci of the ores. The textures of the ore represent a combination of crustification and replacement. Among the later minerals pseudo-eutectic replacement textures are very common, and have been mentioned and figured by various authors.[3] Most prominent are the replacements of tennantite by

[3] Lindgren, W.: Pseudo-eutectic Textures. ECON. GEOL., 25, 1–13, 1930. Ahlfeld, F.: *Op. cit.* Orcel, J., and Rivera Plaza, Gil: *Op. cit.*

stromeyerite, but there are also similar intergrowths of tennantite-chalcopyrite, tennantite-galena, chalcopyrite-sphalerite, and chalcopyrite-proustite. It may be recalled that Burbank has published similar fine textures of stromeyerite and galena and of tennantite and stromeyerite from Bonanza, Colorado. All these are considered to be hypogene.

Summary.—In recent years, Colquijirca, six miles distant from Cerro de Pasco, has been one of the most productive silver mines of the world. The deposit is contained in folded Mesozoic calcareous shale and limestone. Small intrusions of dacite porphyry occur in the vicinity. The folding preceded the mineralization, which is distinctly of epithermal type and was probably effected at temperatures gradually sinking from 200° or 250° C. to something like 100° C. The shale has been replaced by chalcedonic silica, forming a brown chert. Other early gangue minerals are kaolin, dolomite, and ankerite, and their deposition continued during the mineralization to less extent. Barite is a later and abundant gangue, particularly in the copper-silver ores. Pyrite, poor in silver, is the earliest metallic mineral and is followed by sphalerite, enargite, tennantite, galena, and chalcopyrite. Bismuth minerals follow the tennantite. Then follows hypogene stromeyerite, which, with supergene native silver, is the principal mineral in the rich argentiferous ores. Argentite and chalcocite are not abundant. Within a stratigraphic distance of 50 meters are several mineralized beds or "mantos." The lowest is the pyritic manto, poor in silver; above this are beds in which lead and zinc appear in large amount; the highest manto is the richest, with tennantite and stromeyerite. Analyses of wittichenite, stromeyerite and tennantite are presented.

It is held that the association of mantos with differing mineralization within so small a stratigraphic distance cannot be explained by "telescoping," or by differences in depth, but that they are caused by sinking temperature and simultaneous changes in the composition of the solutions. An interesting feature is the latest hypogene mineralization carrying chalcedony, specularite, marcasite, chalcopyrite, and galena. Not much appears to be

known about the uppermost zone of oxidation, except that it seems to be poor and shallow, as shown by the early colonial mining operations on the outcrops; probably it has been subjected to long-continued leaching. But when the descending surface waters reached the stromeyerite zone, they effected a rapid breakdown of this mineral, resulting in the development of native silver on a large scale. For the silver zone does not simply represent a setting free of the silver in tennantite and stromeyerite, but the accumulation of a great deal of this metal carried by the descending solutions.

Laboratory of Economic Geology,
Mass. Institute of Technology,
June 12, 1934.

STRUCTURAL FEATURES OF GOLD DEPOSITS IN CERTAIN INTRUSIVES OF WESTERN QUEBEC.[1]

L. V. BELL AND A. M. BELL.[2]

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INTRODUCTION.

A STUDY of recent gold discoveries related to granitic intrusives in the Abitibi district of Quebec has revealed structural features common to each of the deposits. Although they are markedly similar in their broad structural features, they are found to differ rather widely in a more detailed application of these structural theories. The deposits under discussion are situated in the eastern part of what has been termed the Abitibi Mineral Belt in the townships of Louvicourt, Pascalis, and Tiblemont (Fig. 1). Only those deposits in batholiths and stocks are dealt with, since

[1] Published with the permission of the Director, Bureau of Mines, Quebec.

[2] The writers wish to express their appreciation to Dr. John A. Dresser, Directing Geologist of the Quebec Bureau of Mines, for his critical reading of the manuscript.

these comprise the bulk of the more important discoveries in the Eastern part of the Abitibi Belt.

These deposits are connected with two granitic masses of batholithic dimensions known as the Bourlamaque granodiorite and the Pascalis-Tiblemont soda granite, and with stocks of satellitic nature varying in composition from diorite to granite. Most of the smaller masses are thought to be genetically related

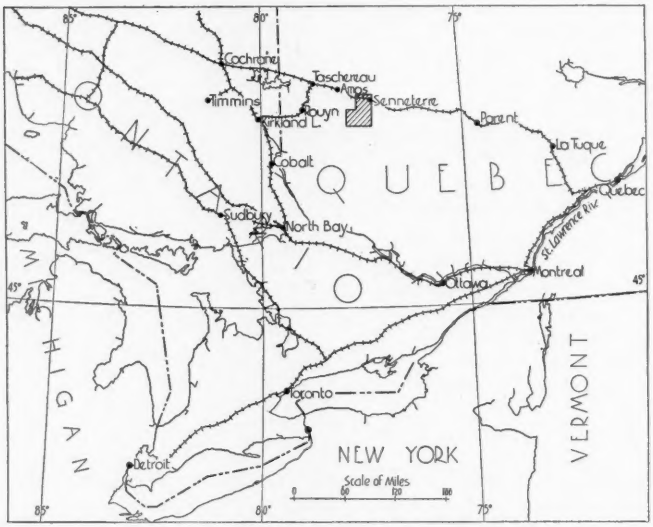

FIG. 1. Index map showing location of district described.

to the larger ones. All of them are intrusive into the predominantly volcanic rocks of the Keewatin, but they occur a relatively short distance north of the belt of Timiskamian sedimentary rocks, with which the gold deposits of the Abitibi Belt are characteristically related. The various intrusive masses together with their associated deposits are shown in Fig. 2.

It will be seen from what follows that in a broad way the localization of the deposits is essentially structural, and that the structural features are dependent on the presence of rocks that will

react quite differently under stress. Generally speaking, this would imply the association together of rocks of different composition and texture. This association may be represented in the contact between a granitic mass and the softer and more altered Keewatin rocks into which it is intrusive; in the presence of in-

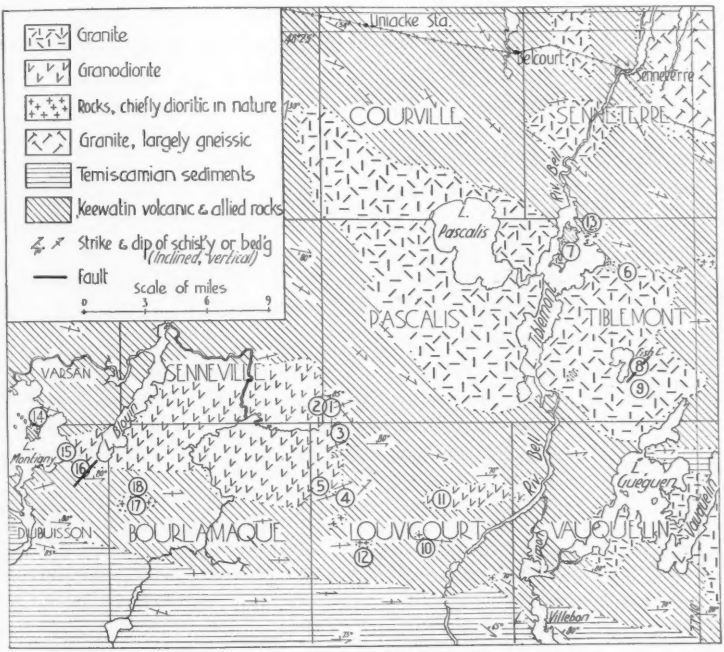

FIG. 2. Geological sketch map showing association of gold deposits with intrusive bodies of the Eastern Abitibi belt.

Location of Gold Deposits (Mining Properties): (1) Beaufor. (2) Matthews. (3) Bussières. (4) Louvicourt Mines. (5) Newroy. (6) Wood-Etcheverry (Murwood). (7) Tiblemont Island. (8) Martyn-Sweet. (9) South Tiblemont. (10) Vicour. (11) Wyeth-Jowsey (Louvre). (12) Metcalfe. (13) J. Smith. (14) Siscoe. (15) Sullivan. (16) Greene-Stabell. (17) Lamaque. (18) Sigma.

clusions of weaker rocks within the hard granitic masses; and by the occurrence of dikes, generally of more basic composition than the granitic rock that they intrude, and of different texture. Structures requisite for gold deposition have been formed where associated rocks of different types have been subjected to external stresses as the result of which one type of rock has yielded selectively by schisting, whereas the one adjacent, of a more competent and brittle nature, has adjusted itself to such deformation by fracturing. The more competent members are the rocks of granitic nature, whereas those less resistant to external forces are, in general, the Keewatin rocks and the few basic intrusives. The deposits are almost invariably in the more massive, fractured rock adjacent to the sheared phases.

It would seem probable that it is in large part the shear zones that have tapped and provided access for the metal-bearing solutions, although in general, they are not themselves the loci of the deposits from such solutions. The solutions are assumed to have arisen along the channels afforded by the steeply-dipping shear zones, or along the contacts of these zones with the more massive rock into the fractures of which they eventually migrated and deposited their loads. In most cases it is apparent that the dip of the individual vein fractures is too shallow to extend to the depth that would be required to tap the vein solutions, although collectively they might do so. Several theories may be advanced for the fact that deposition has for the most part taken place in the more massive, fractured rock rather than in the sheared rock adjacent to it. The flat dip and rather limited lateral extent characteristic of many of the fractures are assumed to be among the factors that localized deposition, in that they would have the effect of damming the rising solutions, whereas no such effect is to be expected in the steeply-dipping shear zones. The shear zones are so diffuse in nature that they would provide but little control by which the solutions might be deposited within them.

That the stresses operative in the development of the gold-bearing fractures were external dynamic forces exerted subsequent to the cooling and solidification of the intrusive masses is re-

vealed, among other evidence, by the regularity of the system of fractures as developed in the Pascalis-Tiblemont granite in Tiblemont township. The fracture pattern is exhibited in the strike of certain dikes and quartz veins by which many of the fractures are defined, and by jointing of the rock. It falls into three definite, steeply-dipping sets striking uniformly in a north, northwest, and northeast direction. There is evidence that movement along the fractures had a strong horizontal component. The north-south fractures are believed to be tension cracks; this would imply compression in a north-south direction, a feature assumed to have been operative in earlier times, as evidenced by the tightly-compressed east-west folds in the Keewatin rocks of the district. As a further indication as to the nature of the stresses, it is apparent that the intense shearing with which some of the deposits in the granitic rocks are associated could have resulted only from the influence of external forces, as distinct from adjustments connected with the cooling and solidification of the granitic magma.

Although the problem as to the origin of the deposits from a genetic standpoint will not be considered here except as it concerns the structural features, it may be said that the constant association which has been found to exist between the location of the gold deposits and that of the granitic and allied intrusives leaves little doubt as to their close genetic relationship. The theory set forth in the present discussion that the deposits are much later than the major period of granitic intrusion and are controlled by fracturing under regional stress subsequent to the solidification of the intrusives, is not here opposed to the theory of their genetic affinity. Study of the intrusives has in a number of cases shown a series of later dikes which the authors are convinced have resulted from differentiation of the parent magma common to both. The dikes occupy fractures in the intrusive rock which in many cases are also occupied by the veins and are evidently of a like origin. This would imply long-continued differentiation in the magma subsequent to its consolidation in that portion of the intrusives now exposed. Further evidence as to the genetic relationships between the several plutonic bodies of the

district and the deposits found within them is provided by a comparative study of the mineralization connected with the Bourlamaque and Pascalis-Tiblemont batholiths. The white quartz veins in the Bourlamaque mass are rich in tourmaline, and commonly they are heavily mineralized with massive aggregations of pyrite, with which most of the gold is associated; chalcopyrite occurs more sparingly than does pyrite. The veins in the Pascalis-Tiblemont granite, on the other hand, are characterized by glassy quartz with little or no tourmaline, and for the most part they are rather barren of sulphide mineralization. Pyrrhotite is more common than pyrite, and galena is reported from some of the veins. Gold occurs typically in visible form as small nuggets or "pin heads" in the quartz. It would appear that the mineralized deposits connected with each of the two intrusions are sufficiently distinctive in character to justify the assumption that they have been derived from separate magma reservoirs, and that such magmas are now represented in the two batholiths.

From the standpoint of their structural relationships and location with regard to the invading rocks, or granitic and allied masses, the deposits may be grouped into three distinctive types, as follows: (1) Deposits within, but along the margins of, the larger intrusive bodies. The group is typified by the deposits along the eastern margin of the Bourlamaque granodiorite in Louvicourt and Pascalis townships. (2) Deposits within the Pascalis-Tiblemont batholith. Certain gold-bearing zones such as those in the vicinity of Fish Lake are more particularly representative. (3) Deposits in smaller intrusive bodies satellitic to the two batholiths of the foregoing. There are several examples in both Louvicourt and Tiblemont townships, and elsewhere.

A number of gold deposits in Louvicourt, Pascalis, and Tiblemont townships are described in subsequent pages. The deposits controlled by various mining companies are not described from the standpoint of their economic importance; rather, they were chosen because they best illustrate the various structural theories that have been advanced. Other properties not described here may prove equally important economically. In general, more

information of a structural nature has been derived from those deposits that have been more extensively developed, particularly by underground methods. Only those deposits situated to the east of Bourlamaque and Senneville townships are dealt with in this paper, since it is with these that the writers are more familiar. A systematic geological survey of the district provided an opportunity for detailed study of the mineral deposits and of their general relationships. The results of this study, including a detailed description of the various deposits, are incorporated in the recent Annual Reports [3] of the Quebec Bureau of Mines, to which the reader is referred.

In order that it might be made more comprehensive, the accompanying map (Fig. 2) illustrates the location not only of the deposits described in the present paper, but several of the better known deposits associated with the westerly continuation of the Bourlamaque granodiorite and its related intrusives in Bourlamaque, Dubuisson, and Varsan townships. It seems likely that these deposits, which occur under similar geological conditions, are similar in broader structural features. It will be seen that in this respect they resemble the Siscoe gold deposit, the structure of which has been worked out by J. E. Hawley.[4] He infers that the structural pattern has resulted under the influence of external stresses having a strong east-west component.

DEPOSITS WITHIN BUT ALONG THE MARGIN OF THE BOURLAMAQUE BATHOLITH.

Exemplified here are certain deposits in Louvicourt and Pascalis townships that occur along the eastern margin of an intrusive body known as the Bourlamaque granodiorite. The granodiorite intrudes Keewatin volcanics, and although the deposits lie in the invading rock they are all within a half mile of the invaded rocks. The association would appear to be largely structural. The relationships indicate that the effects of external forces were

[3] Que. Bur. Mines, Ann. Rept., 1931, Part B; 1932, Part B; 1933, Part B.
[4] Que. Bur. Mines, Ann. Rept., 1930, Part C, pp. 50, 51.

largely confined to the vicinity of the contact between the granodiorite and the less competent Keewatin rocks. Fracturing, with some foliation of the rock, took place along the margin of the more brittle rock of the batholith, whereas the adjacent Keewatin rocks yielded by flowage and selective deformation, by schisting. Generally speaking, the abundant fractures and more limited foliation of the rocks of the border of the batholith give place to massive rock with only "tight" fractures and joints within its interior. There are, however, easterly-trending shear zones in the granodiorite occupied by gold-bearing quartz about a mile from the nearest Keewatin-intrusive contact. The Herbin Lake claims in Bourlamaque township are cited in this connection. Here, however, J. E. Hawley has observed small inclusions of Keewatin schist which led him to think that the top of the batholith was not far above the surface exposed at present.[5] The shear zones in this case might, therefore, be accounted for by the proximity of the Keewatin-intrusive contact in a vertical rather than a horizontal direction. The fact that such pronounced fracturing and shearing is largely confined to the borders of the granodiorite in contrast to the presence of such structures well within the Pascalis-Tiblemont soda granite, is to be attributed, as will be shown later, to the more homogeneous character of the granodiorite.

Although the strike of the vein fractures and foliation along the eastern border of the granodiorite varies somewhat, the prevailing strike is rather uniform and is slightly north of east. This corresponds closely in direction to the regional east-west structure as exhibited in the schistosity of the adjacent Keewatin rocks. The structure of the granodiorite border would imply the action of forces later than those producing the tightly compressed east-west folds of the Keewatin, but causing shortening in the same north-south direction.

The gold-bearing veins and lenses of the granodiorite border almost invariably dip to the south, for the most part at a rather low angle. Their southerly dip is likewise characteristic of the deposits associated with the smaller intrusive bodies of the same

[5] Que. Bur. Mines, Ann. Rept., 1930, Part C, p. 84.

townships (Pascalis and Louvicourt), and would thus appear to be a broad structural feature. The deforming stresses seem to have been exerted in such a manner as to maintain the openings of the southerly-dipping set of fractures so that they were subsequently filled with vein matter. Evidence for this is seen in the tendency, as subsequently shown, for many of the deposits to occupy tension fractures.

The more important veins as yet revealed in association with the granodiorite batholith as a whole, are near its eastern and western ends, whereas few have been found along its sides. Although there may be other factors, such as poorly exposed rock which has hampered prospecting, it is thought that an explanation may be made on structural grounds. Thus, it is assumed that structures more favorable for gold deposition are to be found where the direction of the granodiorite-Keewatin contact is transverse, or at a steep angle to the direction of the regional structure. In other words, more suitable structures were produced where the contact between the two rock types is roughly at right angles with the axis of regional folding. According to this theory, the more promising localities are to be found along the two ends of the intrusive mass or near bends in its sides. This theory is illustrated in Fig. 5, although that figure shows the occurrence of deposits connected with the Pascalis-Tiblemont batholith.

The structural features of the deposits of the eastern margin of the Bourlamaque granodiorite and the characteristics peculiar to each are illustrated by a brief consideration of the Beaufor, Bussières, and Newroy mines.

Beaufor Mine.

The deposits are in granodiorite near where its eastern border bends rather sharply to the west, after which it continues its more northerly course (Fig. 2). The present discussion concerns the northern mineralized zone of this property, on which development has been centered. The veins fall into three sets. The first, and presumably the earliest, is a system of quartz veinlets which occupy well defined fractures with average strike of

N. 65° E. and dip of 60° NW. With the exception of a narrow sulphide vein highly enriched with gold, the veinlets, although mineralized with sulphides, are barren of gold. Secondly, is a system that includes the majority of the veins and principal fractures. It has a strike averaging N. 70° W. and a southerly dip of about 40° or less. Included here is the Matthews vein on which the incline shaft was sunk. The veins of this set commonly exhibit flat, lateral expansions which are invariably short and in no wise interrupt their continuity. The expansions are believed to occupy tension cracks. They are more common on the hanging-wall side of the veins. There is some evidence to suggest that movement along the vein fractures was that of a reverse fault, *i.e.* the south side of such fractures was thrust upward in relation to the north side. Most of the vein fractures of the system under discussion are invaded by a series of narrow trap dikes. Pronounced shearing of these dikes indicates that there were movements along the vein fractures subsequent to the initial fracturing and prior to the deposition of the vein matter. It should be noted that the strike of this series of veins roughly corresponds to that of the assumed granodiorite Keewatin contact (covered at this point), and to one of the directions of schistosity in the near-by Keewatin lavas. Lastly, there is a set of fractures with a dip similar to that of the second type, but with a strike intersecting it at a low angle. The strike is N. 75° E., which about parallels the direction of regional schistosity as displayed by localized shearings in the granodiorite and by the schistosity of the adjacent Keewatin lavas. A short distance north of the vein system, and also to the south in the southern mineralized zone of the property, are strong shearings striking slightly north of east and dipping steeply. The relationships between the dip of the various vein structures and of shear zones in their vicinity are illustrated in Fig. 3. The theory advanced for the development of a structural pattern of this nature is that of external stresses causing shortening in a north-south direction with the direction of easiest relief upward. The northerly-dipping veinlets, and the veins that dip in the opposite direction, correspond

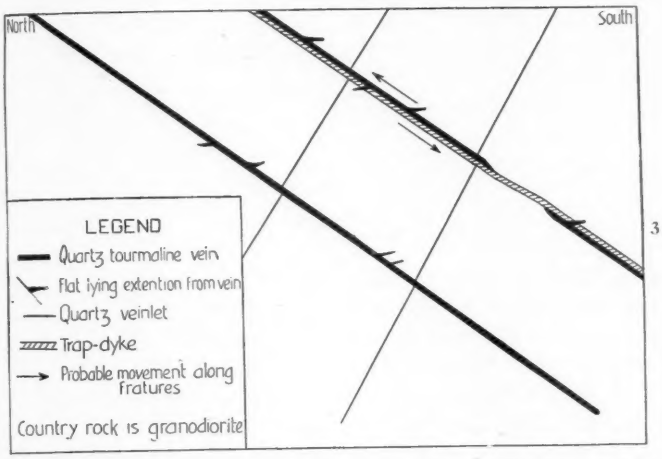

FIG. 3. Diagrammatic section showing attitude of veins and veinlets, Beaufor mine.

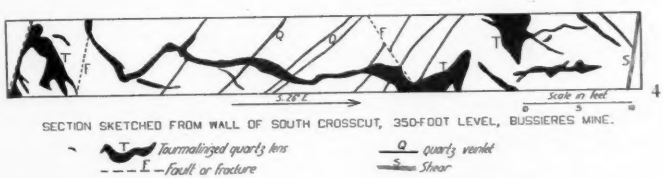

FIG. 4. Section, wall of south crosscut, 350-ft. level, Bussières mine. Country rock is granodiorite.

to the directions of maximum shear; the flat lenses or expansions, to the directions of tension; and the shear zones, to that of flow cleavage. The structure of the Beaufor mine as outlined would appear to apply equally to the Matthews mine adjoining it on the northwest.

Bussières Mine.

The deposit comprises a series of mineralized quartz lenses in sheared and foliated granodiorite near its north-south contact

with Keewatin lavas (Fig. 2). The gold-bearing lenses have been traced in a westerly direction throughout the quarter-mile length of the outcrop in which they occur. Beyond this the rock is obscured by glacial debris so that it cannot as yet be determined how closely they are confined to the border of the batholith. The structural features are as follows: (1) A foliation of the rock, which in many places is sufficiently strong to constitute shear zones. These are developed more or less *en échelon* and between them the rock is more massive, but foliated to some extent. The shearing dips steeply to the north and strikes N. 75°., thus corresponding to the schistosity of the associated Keewatin rocks. (2) A set of mineralized veinlets corresponding in every respect to that of the Beaufor mine, but unimportant economically. They strike as an average N. 60° E. and dip 50° NW. (3) A few faults and fractures with easterly strike and southerly dip; one of the more pronounced of these is a strong fault (apparently reverse) dipping 60° south. (4)The highly irregular, commonly crescent-shaped, gold-bearing lenses, generally characterized by their gentle southerly dip. Although individually of flat dip, there is evidence in one case that a successive series of them, as revealed by stoping, occupy superimposed "benches" to form collectively a zone dipping 30° to the north. The lenses are clearly later than the northerly-dipping mineralized veinlets. The structural pattern is fairly well illustrated in a section from a sketch of the wall of a north-south crosscut in the mine (Fig. 4). It will be seen that the structural elements are similar to those of the Beaufor deposit and are such that the action of similar stresses may be invoked. The major difference lies in the fact that the individual gold-bearing lenses of the Bussières mine occupy the direction of tension rather than one of the planes of maximum shear, as at the Beaufor Mine. A further contrast is provided in the commonly foliated rock of the Bussières Mine and the relatively massive country rock of the Beaufor deposits. The structure of the Bussières may be similar to that of the Louvicourt Mines, Limited, since the two deposits show certain similarities. Development of the latter has not, however, proceeded far enough to establish the structural relationships.

Newroy Mine.

The deposit consists of a principal gold-bearing vein together with several subsidiary lenses that strike about N. 70° E. and dip 60° S. or less. The veins are in granodiorite, but are so close to the southern contact between the batholith and rhyolite breccia (Keewatin) that the principal vein may be expected to dip into this rock at a vertical depth of about 300 feet. Owing to limited underground development, the structural relationships are merely conjectural. That the strike of the veins closely parallels that of the granodiorite border at this point, has been demonstrated. As to their dip in relation to that of the batholith, there would appear to be three possibilities, (1) that the veins occupy fractures branching off from the more steeply-dipping intrusive-Keewatin contact; (2) that the vein fractures parallel the dip of the contact; and (3) that they pass through the contact into rhyolite breccia. The second assumption requires that the granodiorite-breccia contact dip south at about 60°; the others would require a steeper dip. Although specific structural data are lacking, the known features suggest that the structure was evolved under conditions broadly similar to those in the Beaufor and Bussières deposits. Indeed it is probable that the same stresses acting on the granodiorite as a unit were responsible for the structure of the several deposits along its eastern margin. Even though the structure of such deposits varies in detail, in their broader aspects they are alike.

DEPOSITS WITHIN THE PASCALIS-TIBLEMONT BATHOLITH.

A discussion of the Wood-Etcheverry and Tiblemont Island properties, together with the deposits in the vicinity of Fish Lake, will serve to illustrate the essential structural features of the deposits of this class. Although the two former properties are within a half mile of the invaded rocks, and may thus be regarded as related to the border of the batholith and therefore to be classed with the deposits discussed in foregoing pages, it will be shown that they are related to structures within the batholith

rather than to those directly connected with its margin. This does not, however, by any means preclude the probability that deposits purely marginal in character may occur here. The principal discoveries in the Pascalis-Tiblemont batholith are situated in Tiblemont township (Fig. 2). It will be noted that the deposits are all located from a quarter to over two miles from the margins of the batholith. They have but recently been discovered and their commercial importance has yet to be established. Some of them may be found to constitute ore bodies, although not necessarily in the examples cited.

The Pascalis-Tiblemont batholith shows considerable diversity of rock types, although about 90 per cent. of it may be referred to soda granite. Several rock types, including aplite, have resulted from differentiation of the parent magma, but of these diorite is by far the most abundant, especially in the southern and central portions of the batholith; a sheared phase, in particular, is of significance in the localization of the gold deposits. The diorite is in part distinctly older, and in part essentially of the same age as the acid phase. In some localities it has been strongly sheared to form a chloritic rock closely resembling Keewatin greenstone. In addition to these rocks there are several large inclusions or roof pendants of basic Keewatin lavas within the boundaries of the intrusive mass.

The presence within the batholith of these several rocks of varying types, and hence competency, has in some measure modified the uniform deformation of the mass and thus influenced the development of gold-bearing structures. The several deposits that are described as examples will serve to show the close association between the occurrence of mineral deposits in a brittle rock and the proximity of more schistose rock. The explanation for this association may be advanced by elaborating the introductory remarks to the effect that the stresses to which the rocks have been subjected have resulted in the selective deformation by schisting of the basic inclusions (dioritic intrusives and Keewatin lavas) and fine-grained aplite, which in turn has caused the adjacent, more brittle granite to adjust itself to such deformation

by fracturing. Both the vein-filled fractures in the granite and in part at least, the schistosity in the more basic inclusions, are believed to have been caused by regional deforming forces. The theory has already been advanced, and evidence cited, to indicate that the stresses are external and regional in nature and that they involved horizontal shortening in a north-south direction, with pronounced horizontal movements giving rise to a series of fractures that predominate in three definite directions. The main deposits are not, however, directly connected with this uniform fracturing, but rather with fracturing that has been concentrated in zones adjacent to the included masses of schisted material.

It would further appear that the attitude of the contact between granite and more basic rock with relation to the direction of maximum flowage by schisting in the latter rock, has an important bearing on the forming of gold-bearing fractures (Fig. 5). This theory has already been advanced in connection with the deposits of the Bourlamaque granodiorite. In this case in particular, in which deformation was probably greatest in the horizontal plane, differing in this respect from the deformation of the Bourlamaque granodiorite, the most favorable place for concentration of fracturing near steeply-dipping contacts appears to be where the strike of the contact makes a large angle with the direction of schistosity. If such a contact parallels the schistosity, fracturing in the adjacent granite seems to be confined largely to short tension cracks. Near more flatly-dipping contacts the brittle rock may be fractured into angular blocks and the fractures filled with quartz, as at the Wood-Etcheverry deposit.

Four of the more important gold occurrences known in 1933 will serve to exemplify the structural factors controlling their deposition.

Wood-Etcheverry Property.

The deposit is in soda granite on the north side of a large pendant of Keewatin lava. It is slightly more than a quarter mile south of the northern contact between the batholith and the Keewatin rocks. Gold occurs in an irregular stockwork of steeply-dipping veins occupying fractures in a shattered zone in

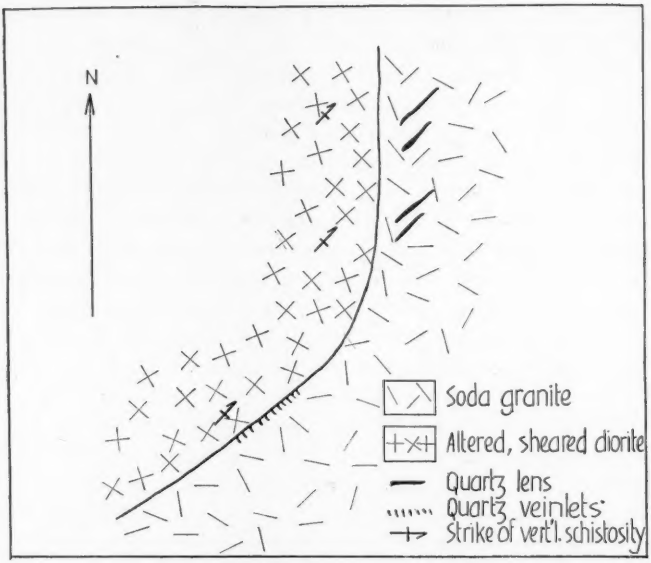

FIG. 5. Sketch illustrating relation of vein fractures to direction of contact between rocks of varying competency.

the granite adjacent to the schistose lava. Diamond drilling has shown the inclusion of lava to dip flatly away from the vein zone, suggesting that the lava once formed a capping over it. The fact that the mineralized zone containing the highest percentage of quartz appears to have but a limited vertical extent may imply that, in this case, damming of ascending solutions beneath an overlying capping was a factor in localizing gold deposition.

Tiblemont Island Mining Company.

On Tiblemont Island, some two miles west of the above deposit, are numerous gold-bearing quartz lenses and stringers in granite of similar nature, located at a distance of approximately a half mile south of the northern margin of the mass. A close as-

sociation is apparent between the lenses and irregular inclusions of chloritic schist. The lenses strike in a general east-west direction parallel to the vertically-dipping schistosity of the related schistose rocks, but have a general dip of 60° N. They occur in fractured granite, for the most part near the east or west end of a schistose inclusion.

Fish Lake Deposits.

A third locality in which there are gold-bearing veins is in the vicinity of Fish Lake in the southern part of Tiblemont township. The deposits are within the intrusive at a distance of more than two miles from its border. The soda granite here intrudes masses of more basic and now highly altered rock of dioritic nature. Intrusive into both are irregular masses of fine-grained aplitic rock, which in places is strongly sheared. A series of northeasterly-trending faults are indicated in the vicinity.

South Tiblemont Mining Company. The deposit under development consists of a series of gold-bearing quartz lenses and stringers in lenticular, fractured zones in soda granite near a band of altered, dioritic rock. Locally, the contact between these two rock types strikes north-south, whereas the vein fractures strike northeast-southwest and thus angle into it on the southwest (Fig. 5). The veins of the fractured zone parallel the strike of the schistosity in the dioritic rock, and also the indicated faulting of this vicinity. The gold-bearing quartz occupies fractures a short distance removed from the granite-diorite contact and disappears to the northeast as the fractures in the granite die out.

Martyn-Sweet Property. Similar features are revealed in a more recent discovery a mile to the north. In the soda granite, slightly removed from its northerly-striking contact with a body of schistose diorite, is a zone of quartz lenses some 30 feet in width. The quartz-bearing zone parallels the border of the diorite, but the individual lenses within it strike parallel to the schistosity of the diorite.

DEPOSITS IN MINOR INTRUSIVE BODIES.

Broadly speaking, the structural features of this division may be regarded as the converse of that just considered. It was shown that localization in that case was effected by inclusions of softer and less competent rocks within the hard and brittle granite. In the present case the deposits are connected with relatively small masses of the harder and more competent intrusive rocks within the much more extensive and weaker Keewatin beds. Evidence will be cited to show that at least one of the small stocks with which there is related gold mineralization was involved in the later folding of the Keewatin rocks. Structure must be regarded, however, as only one of the factors governing localization of the deposits. A more important factor may be a definite genetic association that is believed to obtain between the deposits and the small intrusive bodies.

The principal stocks satellitic to the larger intrusive bodies, together with their related mineral deposits, are indicated on Fig. 2. Some of these are so similar petrographically to one or the other of the two batholiths that they are definitely regarded as cupolas connected with them at depth. The others are in general much more altered, and are chiefly of dioritic nature but of somewhat varying composition. They resemble certain border phases of the batholithic masses, and may be an early, more basic phase of the same intrusive activity. The fact that they are commonly of more basic nature may be due to the relatively greater assimilation of the invaded rock by minor intrusive bodies. The structural features of the deposits connected with such intrusives are exemplified in the Vicour, Wyeth-Jowsey, Metcalfe, and J. Smith properties.

Vicour Property.

The country rock is fractured quartz diorite which lies in sheared contact with diabase. A second shearing occurs in the quartz diorite 250 feet south of the diabase; the deposits lie in the fractured rock between the two shear zones. The mineralized zone has been traced along the strike of the related shearing in a

direction N. 75° W. for a distance of about 2,000 feet. The deposits seem to be largely confined to a width of about 30 feet bordering the southern shear zone. They consist of a highly irregular series of mineralized quartz lenses which, in the aggregate, dip flatly to the south. The structure is that of a block of massive, brittle rock sandwiched between two shear zones along which there has been differential movement. The block has been fractured by these movements, and subsequently quartz and mineral-bearing solutions were introduced into the fractures. The flat southerly dip characterizing the vein fractures would indicate that movement along the shears has a vertical component, with the south side being thrust upward in relation to the north side. Such movements would be manifested in the opening of southerly-dipping tension fractures, particularly near the southern shear zone.

Wyeth-Jowsey Property.

The structural features and conclusions as inferred from a study of the Vicour would appear to apply equally to the Wyeth-Jowsey deposits except that in this case there is a more uniform system of fractures. The mineralized zone has as yet been traced for only a relatively short distance along the east-west strike. As in the case of the Vicour deposit, it consists of a series of gold-bearing quartz lenses in fractured rock lying between strong east-west shear zones. The country rock is a stock of granodiorite so similar petrographically to the Bourlamaque granodiorite that it is regarded as a cupola connected with it under an intervening capping of Keewatin greenstones (Fig 2). A test-pit in the mineralized zone reveals a uniform set of east-west fractures dipping 65° S. Some of these are filled with thin lenses of quartz, but quartz occurs for the most part as irregular lenses occupying subsidiary fractures dipping more flatly, about 45° S. A section as sketched from the east wall of the test-pit (Fig. 6), illustrates the attitude of the system of fractures and of the related quartz lenses.

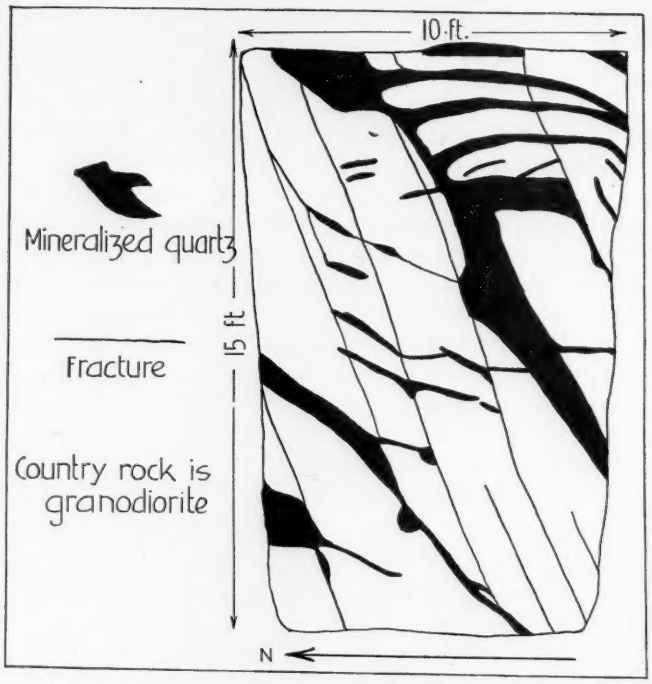

FIG. 6. Section, east wall of test-pit, Wyeth-Jowsey property.

Metcalfe Property.

The deposit is in a dark, altered and chloritic rock that exhibits a few bluish, opalescent eyes of quartz. This rock, termed quartz diorite, is in intrusive contact with Keewation rhyolite. The size of the stock cannot as yet be determined. The "discovery" vein, one foot in thickness, occupies a well defined fracture in the otherwise fairly massive quartz diorite. It strikes N. 55° E. and dips 50° SE. Extending out from the vein fracture and limited to its footwall, are a number of thin, flat expansions or lenses, which are repeated at vertical intervals of about four feet. They are closely limited to the controlling vein

fracture in their lateral extent. Gold and related mineralization is largely confined to the flat lenses, and the vein itself appears to be rather barren. The lenses are assumed to occupy tension fractures that have been opened up by upward movement on the south side of the vein fracture. Such movement would result in the tension fractures being confined to the footwall side of the vein.

The three examples cited serve to show that in each case the relevant fracturing involved movement such that the south side of the fractures was thrust upward in relation to their north side. As already shown by the other examples given in the same townships of Pascalis and Louvicourt, displacements requiring relatively similar movement have for the most part been postulated. This similarity in the detailed structural effects in a number of cases throughout so extensive an area would suggest that they had been influenced by common stresses of broad, or regional character.

J. Smith Property.

Gold deposits have recently been found in a small stock of soda granite about a mile north of the major batholith in Tiblemont township. There is so marked a similarity petrographically between the rock of the two masses that the smaller one is regarded as a related intrusive. The rocks surrounding the stock are steeply-dipping schisted lavas. Gold occurs both in quartz veins in the granite and in pyrite replacements accompanying the veins. Both the gold-bearing veins and a series of related, lamprophyric dikes occupy a system of regular and persistent fractures in the granite. The fractures occur in two steeply-dipping sets which intersect at an angle of 15° to 20°. Generally speaking, one set strikes S. 70° E. parallel with the regional folding and schistosity, and the other set strikes S. 55° E. That there has been recurrent movement along these fractures is seen by the fact that all dikes following them have been strongly sheared. In every case the movement is principally horizontal, the north side moving west with respect to the opposite wall. The fractures filled by veins and dikes are nearly straight and very persistent. The fracturing

in this instance, as in the case of the deposits previously examined, seems to be due to a brittle body having yielded by fracturing in adjusting itself to the deformation of the lavas which have yielded by schisting. The general parallelism between the fractures and the axis of folding in the near-by lavas suggests that the granite may have been actually involved in some of the folding.

SUMMARY AND CONCLUSIONS.

In the foregoing it has been shown that gold deposits in the plutonic rocks of the eastern part of the Abitibi Belt of Western Quebec are characterized by well defined structural features. The theory is advanced that although the deposits are genetically related to the intrusive masses in which they occur, a more specific control for mineral deposition is provided by structural factors, notably fracturing under certain limiting conditions. Such structural features favorable to gold deposition in the intrusive rocks have resulted under the influence of regional dynamic stresses effective subsequent to solidification of the magma, and are not connected with structures dependent upon its cooling and contraction. The uniformity in the fracture pattern throughout the various invading masses and in the structure of the invaded rocks demonstrates the existence of a broadly similar strain throughout. Structures requisite for gold deposition have resulted under the influence of regional deformation of associated rocks of different composition and texture which, as they possess a varying degree of competency, will react differently. Considered broadly, the gold-bearing fractures occur in more massive and brittle intrusive rock, and are dependent on the proximity of weaker rocks that have yielded more readily to schisting. The gold-bearing fractures may in most cases be regarded as having resulted from adjustment of the massive rock to flowage in the schistose rock. The conditions requisite for such structures are represented in the contact between brittle intrusive rocks and the schistose and more altered invaded rocks, and also in the occurrence of inclusions of weaker rocks within the invading masses. A feature of possible significance is the tendency for more favorable fractures to de-

velop in those places where the contact of the massive rock makes a large angle with the axis of folding, or with the direction of schistosity in the weaker rocks.

From the standpoint of their relationship to the various intrusive masses, the deposits may be regarded as belonging to three structural units. The deposits of each of these units have structural characteristics which in some measure are peculiar to each, but which in a broad way are applicable to all. Their classification is as follows: deposits along the margin of a batholith where bordered by weaker, volcanic rocks; deposits *within* and also near the margin of a batholith, but chiefly dependent upon internal features, i.e., features peculiar to the interior of the batholith; and lastly, deposits in minor intrusive masses regarded as satellitic to the two batholiths.

BUREAU OF MINES,
QUEBEC, QUE.,
NOV. 23, 1934.

THE INFLUENCE OF TERTIARY INTRUSIVE STRUCTURAL FEATURES ON MINERAL DEPOSITS AT JAMESTOWN, COLORADO.[1]

E. N. GODDARD.

INTRODUCTION AND ACKNOWLEDGMENTS.

THE methods developed by Cloos and Balk[2] for using the internal structural features of igneous bodies to work out the mechanics of intrusion have been applied with considerable success to numerous batholithic intrusions. These methods are based on the assumption that the minerals that crystallize during flowage will show a linear alinement parallel to the direction of flowage. The mapping of this linear structure and related effects of intrusion has given important information regarding the subsurface shapes of many igneous bodies and the directions of emplacement.

In June, 1932, Prof. Frank F. Grout, of the University of Minnesota, visited the Jamestown district and instructed the writer in the field technique of the Cloos method. This method was then applied to pre-Cambrian granites and Tertiary stocks and dikes, and the results demonstrated that the Tertiary stocks had a marked influence on the development and distribution of the mineralized fissures. An attempt to present the results of this study, however, soon proved that the strictly igneous structural features had to be correlated and contrasted with the regional structure, and that a knowledge of the sequence of vein deposition was also essential. The original scope of the paper, therefore, was expanded to include, in the first part, the geologic

[1] Published by permission of the Director, U. S. Geological Survey, the Colorado State Geological Survey Board, and the Colorado Metal Mining Fund.

[2] Balk, Robert: Primary Structure of Granite Massives. Geol. Soc. Amer. Bull., vol. 36, pp. 679–696, 1925. See also a brief description by Grout, F. F.: Petrography and Petrology, pp. 29, 30, 197, McGraw-Hill Book Co., 1932.

setting of the district, an outline of both regional and local structural features, and a brief description of the ore deposits, with special emphasis on their close genetic relation to the Tertiary intrusives. The second part deals with the structural features of the Tertiary intrusive stocks and the writer's interpretation of their influence on local structure and the distribution of the ore deposits.

Field work in the Jamestown district was done by the writer during the summers of 1930, 1932, and 1933, under the co-operative plan of the U. S. Geological Survey, the Colorado State Geological Survey Board, and the Colorado Metal Mining Fund. During this time, Mr. T. S. Lovering, of the U. S. Geological Survey, devoted a few days each month to supervising the work at Jamestown, and he has given the writer valuable advice and criticism both in the field and in the office.

LOCATION, HISTORY, AND PRODUCTION.

The Jamestown mining district lies in the Colorado Front Range, 4 to 8 miles west of the plains and 35 miles northwest of Denver. It ranges in altitude from 6,300 to 8,600 feet. Although the production has not been large, the district is of considerable interest because of the variety of its rocks and minerals and because it lies at the extreme northeast end of the Colorado mineral belt. Gold was first discovered in the district in 1865, and since then there has been an intermittent production of gold, silver, lead, and fluorspar, with an aggregate value of about $6,000,000.

GENERAL GEOLOGY.

The Jamestown district is entirely within the pre-Cambrian complex of the Front Range (Fig. 1). The nearest sedimentary rocks lie about a quarter of a mile to the east, where Pennsylvanian red beds rest on the pre-Cambrian and dip about 35° E. It seems probable that these red beds at one time covered the Jamestown district, for scattered fragments of red sandstone still lie on some of the flat-topped hills.

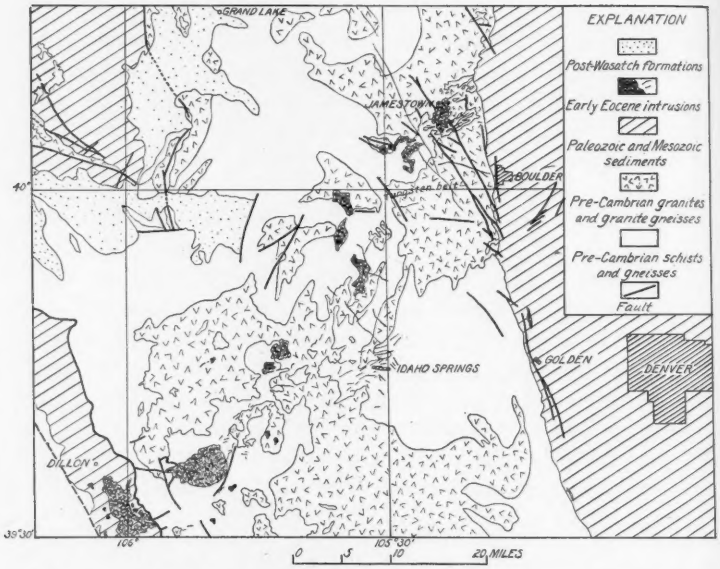

FIG. 1. Sketch map of the Front Range showing the location of the Jamestown district with respect to the regional structure. (From map compiled by T. S. Lovering.)

Pre-Cambrian.—The pre-Cambrian rocks consist of highly metamorphosed schists of sedimentary origin (Idaho Springs formation), which have been intruded by the middle pre-Cambrian Pikes Peak and Silver Plume granites. The extreme southern and southeastern parts of the district are occupied by biotite schist, which has a general N. 60°–70° E. strike, and a steep southeast dip. The remainder of the district is largely made up of granite containing abundant stringers and lenses of schist that also trend N. 60°–70° E.

Tertiary.—This pre-Cambrian complex was intruded by a series of Tertiary igneous stocks and dikes ranging from diabase to alaskite in composition, and believed to be Eocene.

The earliest of the intrusive masses is a strong northwestward-

trending diabase dike which occurs west of the mineralized area and has no apparent relation to the ore deposits. Subsequently the central part of the district was invaded by a large, roughly rectangular stock of hornblende granodiorite, about 1½ by 2½ miles in horizontal dimensions. This was followed by a smaller stock of quartz monzonite porphyry, which closely resembles the Lincoln porphyry[3] of the Leadville mining district. This roughly circular stock, about three-quarters of a mile in diameter, was intruded on the north border of the granodiorite. Associated with it is a system of radial dikes of the same material (Fig. 2). Surrounding the two stocks, but mostly confined to the east side, is a series of porphyry dikes of northeast strike and southeast dip, which appear to be younger than the stocks. They include fine-grained quartz monzonite porphyry, bostonite porphyry, and alaskite porphyry, which were intruded in the order named.

The close relation between these Tertiary intrusives and the ore deposits is indicated by the facts that they are co-extensive and that in other parts of the Front Range, where structural conditions are favorable for metallization but Tertiary intrusives are absent, there are no ore deposits.

STRUCTURE.

Regional structure.—The regional structure of the Front Range has been concisely presented by Lovering.[4] During the Laramide revolution regional compression in a southwesterly direction produced a system of strong, persistent northwest faults throughout the Front Range (Fig. 1). Many of these faults can be traced for 10 miles or more, and nearly all are downthrown to the southwest. This system includes thrust-faults of large magnitude, some of which have displacements of several

[3] Emmons, S. F., Irving, J. D., and Loughlin, G. F.: Geology and Ore Deposits of the Leadville Mining District, Colo. U. S. Geol. Survey Prof. Paper 148, pp. 46–48, 1927.

[4] Lovering, T. S.: The Structural Relation of the Porphyries and Metalliferous Deposits of the Northeastern Part of the Colorado Mineral Belt. Ore Deposits of the Western States, pp. 301–307. Am. Inst. Min. Eng., 1933.

miles. Three persistent northwest faults of this system occur in the Jamestown district, and one of them is cut by the large stock of granodiorite. This relation of the northwest faults to the Tertiary intrusives is borne out in the Montezuma district, on the west side of the Front Range, where the Williams Range thrust-fault is cut by a Tertiary quartz monzonite stock.[5]

In discussing the structure of the Front Range, Lovering[6] points out that the northeastward-trending porphyry belt of north-central Colorado is "nearly at right angles to the direction of regional compression," and suggests that its position is due to "tensional forces of some magnitude" that "were present during the folding of the region."

The porphyries are clearly later than the strong northwest faults, and therefore the vein fissures of the Jamestown district, which are post-porphyry, were formed after the major deformation of the Laramide revolution was completed. In a few places there are small pre-porphyry fault fissures of northeast trend, characterized by the same red breccia which is typical of the strong northwest faults, but they are barren silicified zones and are relatively scarce. Therefore, it seems probable that the regional stresses played a minor part in the formation of the vein fissures of the Jamestown district.

Local Structure.—There are in the Jamestown district two major systems of fault fissures that are occupied by the ore deposits—a northwest system, which is in general the earlier, and a northeast system. The northwest system is mostly confined to a northwestward-trending belt about half a mile wide and 2½ miles long, on the southwest side of the quartz monzonite porphyry stock (Fig. 2). In this belt there are two major zones of fracturing: one, represented largely by breccia zones, trends N. 65° W. along the southwest border of the stock and extends into the pre-Cambrian granite on both sides; the other, represented chiefly by veins, trends N. 40° W. and lies one-quarter to one-

[5] Lovering, T. S.: Williams Thrust Fault (abstract). Geol. Soc. Amer. Bull., vol. 39, no. 1, pp. 173–174, 1928; Geology and Ore Deposits of the Montezuma Quadrangle, Colo. U. S. Geol. Survey Prof. Paper 178 (in press).

[6] Lovering, T. S.: *Op. cit.*, Ore Deposits of the Western States, p. 304.

half a mile south of the border of the stock. At the intersection of these two zones the brecciation is stronger and more extensive than in the rest of the belt. The veins and breccia zones in this belt dip steeply northeast or southwest, and the angle of movement is also steep in the few places where it can be determined,

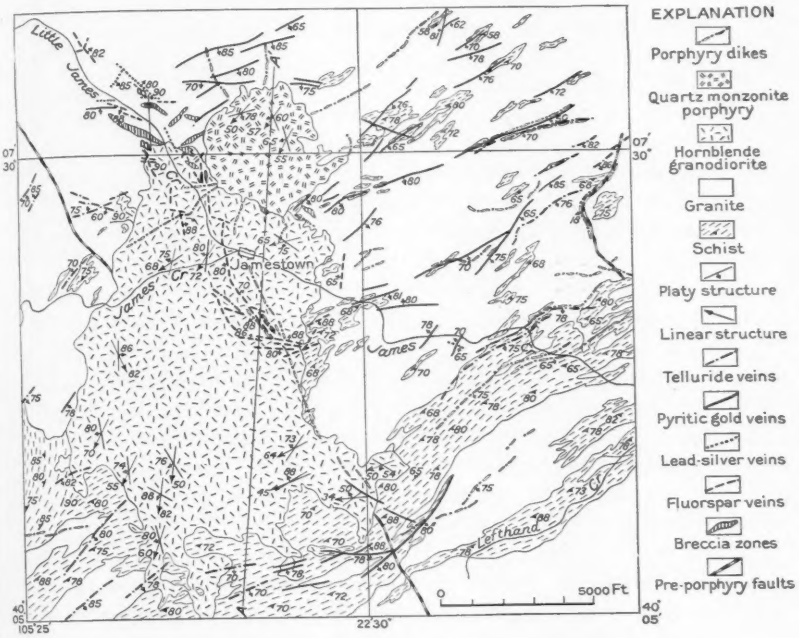

FIG. 2. Geologic map of the Jamestown district, showing the platy and linear structure of the Tertiary stocks and the distribution of the various types of ore deposits. *A–A'*, *B–B'*, lines of sections shown in Figs. 6 and 3.

with the downthrow on the southwest side. There are a few prominent exceptions to the general northwest trend of the breccia zones and veins in this belt. Two strong northeastward-trending breccia zones occur on the west border of the stock, and

one-half mile to a mile southeast of the stock there is a set of fractures that trend northeast and north and are related to the N. 40° W. veins. The granite fragments in the breccia zones are commonly cemented by small amounts of either silica or fluorspar, but in some places are uncemented. The granite and granodiorite throughout this belt of breccias and veins is more or less fractured and sericitized, even where the faults are widely separated.

The fault fissures of the northeast system are more widespread and are filled by veins throughout the mineralized area, but they are stronger and more persistent on the east side of the porphyry stocks. The predominant strike is N. 60°–70° E., and the dip 50°–80° SE. In general, the trend of these faults is parallel to the local schistosity, and several fault fissures that contain important veins lie along the contacts of schist stringers with the granite. With few exceptions, these faults show movement down and to the southwest on the southeast sides, but the displacement has been commonly not more than 10 to 20 feet. The fault fissures of this system are occupied by porphyry dikes of four different kinds and by veins that are younger than the dikes and represent at least two stages of mineralization. The faulting in the northeast system must have extended over a considerable length of time. In many places these faults have reopened along the walls of porphyry dikes. Although the strong regional pre-porphyry compression had largely subsided before these faults were formed, there is no evidence of any post-porphyry relaxation, and it seems probable that mild compression in a northeasterly direction continued throughout this period.

MINERAL DEPOSITS.

The mineral deposits of the district are of four distinct types. Named in the order of age, the oldest first, they comprise fluorspar veins and breccia zones, lead-silver deposits, pyritic gold veins, and gold-telluride veins. These mineral deposits are grouped around the quartz-monzonite stock in a roughly zonal arrangement, with the oldest tending to be closest to the stock

and the others successively farther away (Fig. 2). As indicated by the following description, these deposits have an unsymmetrical and rather irregular arrangement around the quartz-monzonite stock.

Fluorspar Deposits.—The fluorspar deposits occupy the northwestward-trending veins and breccia zones and the few northeasterly breccias and veins of north and northeast trends. The vein filling and the breccia matrix consist mainly of dark-purple fluorspar, with some pyrite, galena, chalcopyrite, and coarse-grained glassy quartz.

The fluorspar breccia zones are of particular interest because they differ from most other fluorspar deposits and from the other deposits in the district. Many of the fluorspar breccia zones are parts of larger barren breccia zones (Fig. 3). The large barren

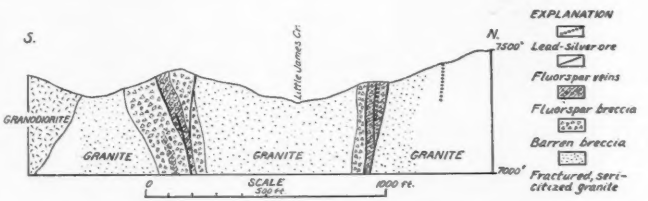

FIG. 3. Section along line *B–B'*, Fig. 2 (upper left), through the Emmet (left) and Argo (right), breccia zones, showing the distribution of the fluorspar ore.

zones are 50 to 200 feet wide and 500 to 2,000 feet long. They consist of slightly silicified granite breccia, which contains small amounts of finely disseminated pyrite. Within the barren zones there are large lenticular areas and also small stringers or veins of breccia cemented by fluorspar. The fluorspar is a rather friable, sugary, dark-purple material, and has to a large extent replaced the ground-up granite between the granite fragments (Figs. 4, 5). In some places only small amounts of the ground-up material have been replaced, but in others the entire matrix is fluorspar, and even parts of the fragments have been replaced.

Within the fluorspar breccia there are high-grade veins 1 to 3 feet wide, which generally trend about north-south or east-west. These veins do not represent a second generation of fluorspar filling fractures in early material, but are high-grade zones which merge into low-grade breccia and differ from it only in the absence of granite fragments. It would appear that the fluorine-

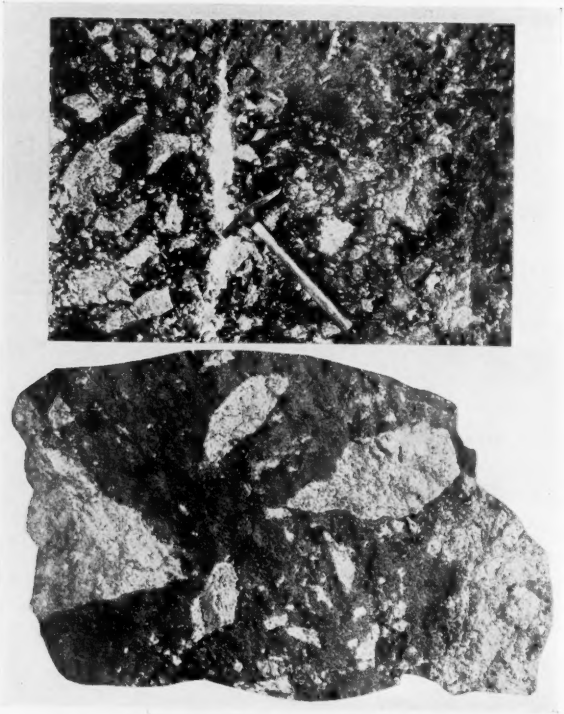

FIG. 4. Underground view of a part of the Argo fluorspar breccia zone. The light-gray fragments are granite; the dark-gray matrix is a mixture of sugary fluorspar and ground-up granite. The greater the amount of granite in the matrix the lighter the color.

FIG. 5. Specimen of fluorspar ore from the Argo mine, one-sixth natural size. Light fragments are granite; dark matrix is nearly pure sugary fluorspar.

bearing solutions came up along the more open channels in the breccia zones and deposited rather pure spar, then gradually soaked out into the surrounding breccia and deposited more fluorspar by replacement of the breccia matrix. It seems probable that the fluorine solutions were derived from the quartz-monzonite magma, for fluorspar is an abundant primary constituent in small pegmatite dikes within the stock itself and in miarolitic cavities.

The fluorspar breccia zones are generally of low grade, containing 25 to 50 per cent. CaF_2, but the veins in many places contain 70 to 85 per cent. CaF_2, and in a few places as much as 90 per cent. The impurities are chiefly ground-up wall rock, quartz, and pyrite.

Lead-Silver Deposits.—The lead-silver deposits are largely associated with the fluorspar deposits in an area of about one-half square mile on the west border of the quartz-monzonite stock. They occur as lenticular pipes in or bordering the fluorspar breccia zones, or in northwestward-trending veins near-by. The pipes consist of irregularly intergrown masses of argentiferous galena, argentiferous gray copper, and auriferous chalcopyrite and pyrite, mixed with varying amounts of fluorspar. The veins contain galena, chalcopyrite, and pyrite in a gangue of glassy quartz. The lead-silver ore bodies are clearly later than the great bulk of the fluorspar, but some coarse-grained fluorspar occupies cavities in the lead-silver ores.

Pyritic Gold Veins.—The pyritic gold veins fill the fault fissures of northeast trend and southeast dip (Fig. 2). They occur chiefly in a zone half a mile wide, 1 to 2 miles east of the quartz-monzonite stock, but also along the north and northwest border of the stock, and a few are scattered to the southwest. The vein filling is mostly coarse-grained pyrite or chalcopyrite in a gangue of glassy, milky, or sugary quartz. The gold occurs free or is associated with the pyrite or chalcopyrite. These veins are mostly later than the lead-silver deposits, although some of the low-grade veins close to the stock may be earlier. In the Durias mine, 1¼ miles southeast of the stock, a pyritic gold vein cuts a lead-silver vein.

Gold-Telluride Veins.—The telluride veins also occupy fault fissures of northeast trend but are generally a little farther from the quartz monzonite than the pyritic veins (Fig. 2). They are scattered along the eastern edge of the mineralized area and also along the south and west borders of the granodiorite stock. These veins contain gold tellurides (chiefly sylvanite) and finely disseminated pyrite in a gangue of gray jaspery or horn quartz. They are clearly later than the pyritic gold veins. In the Golden Age mine a high-grade pyritic gold vein is cut by a high-grade gold-telluride vein. In a few places sylvanite is present in a pyritic gold vein, or even in a lead-silver ore body, but in such places it occurs in vugs and is the latest metallic mineral deposited.

STRUCTURAL RELATIONS OF MINERAL DEPOSITS TO TERTIARY STOCKS.

It is difficult to account for the irregular distribution of the ore-filled fissures by the regional stresses that operated during the Laramide revolution. Although regional stresses played a small part in the formation of these fissures, it seems probable that local forces were the controlling factor. As the Tertiary intrusives are so closely related to the ore deposits, it is logical to suppose that the stresses operating during the intrusion of these masses were effective in the formation of the ore fissures. The scarcity of northeastward-trending fluorspar veins, the general absence of later veins within the granodiorite and quartz-monzonite masses, and the radial arrangement of dikes around the quartz monzonite, also point to the development of the fissures by the intrusion of the compound stock. If numerous fissures had been developed before the intrusion of the stocks, some of them should contain dikes of granodiorite and of quartz monzonite; furthermore, if the mineralized fissures are due to some cause other than intrusion, they should cut the stocks or at least show some consistent deflection around them.

In determining the manner of intrusion of these Tertiary masses, the Cloos method of mapping the internal structural features proved a valuable aid. These internal structural features

are shown in Fig. 2, in which the strike and dip symbols indicate the platy or flow structure, and the arrows and numerals indicate the direction of pitch of the linear alinement or stretching of the magma.

Stresses Associated with the Granodiorite Intrusion.—In the granodiorite stock these structural features seem to indicate a roughly elliptical cylindrical mass that pitches about 60°–70° SSW. (Fig. 6). The mineral alinement and the related intrusive

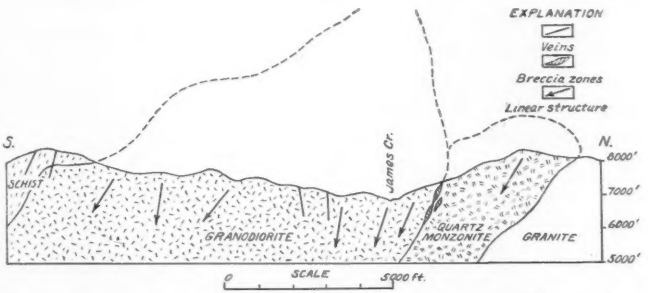

FIG. 6. Section along line *A–A'*, Fig. 2, through the two Tertiary stocks, showing the pitch of the linear structural features and the supposed subsurface shapes of the igneous masses.

structural features all indicate that during emplacement the magma moved upward in a N. 15° E. direction at an angle of about 65°.

The well-developed platy structure in the granodiorite suggests that the roof of the stock was several thousand feet above the present surface, and it is possible that the magma broke out at the old surface, about 5,000 to 6,000 feet above the surface of today. The elongate surface-shape of the granodiorite body (Fig. 2) suggests that the magma made its way up along a fracture-like opening or perhaps a combination of fractures. It is quite possible that the junction of the early northwest fault with the northeast schist and granite contact was the controlling factor in localizing the granodiorite mass. An analysis of the shape of the

body [7] shows that, at the time of intrusion, the axis of greatest external stress resisting the intrusion was parallel to the present linear structure, the intermediate stress was parallel to the long horizontal dimension of the stock, and the direction of least stress was parallel to the shortest dimension. Thus, the magma would tend to widen its channel by pushing outward in the directions of least compressive stress, which were S. 75° E. and N. 75° W. However, the yield to this force was not the same on both sides. On the west side nearly solid granite extends for 10 to 15 miles to the west, but on the east side there is a comparatively weak mixture of schist and granite which ends within a few miles against the incompetent zone of sedimentary rocks that forms the foothill monocline. Thus it would appear that most of the expansion of the granodiorite mass took place to the east, and an active force was exerted in a S. 75° E. direction. The brittle rock subjected to this stress would tend to break along lines at angles of slightly less than 45° to the direction of force.[8] Thus, east of the stock, systems of fractures trending about N. 65° E. and S. 35° E. would probably be developed. However, on the east side of the stock the schist stringers and lenses strike about N. 65° E., making the rock in this direction weaker than in the other. As a result, strong persistent fractures developed in a N. 65° E. direction, and short minor fractures in a southeast direction. West of the stock, both southwest and northwest fractures were formed, but they are not abundant and with a few exceptions are small.

Many of the persistent northeast fractures were soon occupied by porphyry dikes. The linear structure in these dikes pitches 20°–60° SW., suggesting that they came from the same general source as the stock. Continued deformation, stimulated by a component of regional stress and possibly by a further push of magma from below, reopened many of the old fractures and formed numerous new ones.

[7] Stevens, Blarney: The Laws of Intrusion. Amer. Inst. Min. Eng., Bull. 49, pp. 1–23, 1911.

[8] Lovering, T. S.: The Fracturing of Incompetent Beds. Jour. Geol., vol. 36, no. 8, pp. 709, 717, 1928.

Stresses Associated with the Quartz-Monzonite Intrusion.—The quartz-monzonite stock was intruded after the solidification of the granodiorite. In this stock the internal structure indicates a somewhat funnel-shaped mass that pitches about 55° SW. (Fig. 6). During emplacement, the magma apparently moved upward at this angle in a northeasterly direction and came up along the under side of the granodiorite mass. The contact of granodiorite and granite formed a plane of weakness along which it was easier for the quartz-monzonite magma to force its way than within the granodiorite mass itself. Dips of 80° along the southwest contact of the quartz-monzonite stock suggest that the magma near the roof turned up almost vertically near the end of the emplacement process and transgressed the north border of the granodiorite mass. The striking system of radial dikes around the quartz-monzonite stock is additional evidence of this final upward push. The platy structure in the stock is poorly developed and suggests that the roof was not far above the present surface. The linear structure in the radial dikes is nearly horizontal, suggesting that the magma moved out into the fractures from the vicinity of the adjacent part of the stock.

Figure 2 shows that the belt of breccia zones has a northwest trend, at right angles to the direction of flow of the quartz-monzonite magma, and that the breccia is confined mainly to the southwest and west borders of the stock. It seems probable that these breccias were formed as a result of a combination of upward force and drag developed during the emplacement of the stock. The magma, moving upward in a northeasterly direction, tended to push upward and pull slightly apart large blocks of the wall rock along its southwestern border. Within the breccia zones fragments have apparently been moved successively higher toward the north side, and although the displacement between adjacent fragments has been small, the breccia zones were sufficiently wide to take up a large amount of movement. The belt of breccia zones is more strongly developed and extends farther out to the west of the stock than to the southeast. This can be

accounted for by the fact that on the west side the rock is all granite, which would hold an open breccia, whereas on the southeast there is a large amount of schist, which would take up the movement by crumpling and would be much less likely to form an open breccia. The strong northeastward-trending breccia zones on the west side of the stock form the northwest and southeast boundaries of a large granite block, and their formation evidently acted to release the strain between the granite pushed up by the stock and the granite mass to the west. It is probable that similar northeastward-trending breccias would have been formed on the southeast side of the stock also, had it not been for the small bordering schist area (Fig. 2), which took up most of the movement by shearing and crumpling.

In the Skunk tunnel, at the contact of the two stocks, there is a breccia of granite, silicified schist, and granodiorite fragments cemented by quartz monzonite. This indicates that at least some and probably a large amount of the breccia adjoining the stock was sealed by the quartz-monzonite magma. With the old plane of weakness partly sealed, a continued pressure would cause fracturing along other near-by planes of weakness. Thus, one-quarter to one-half mile south of the stock, the N. 40° W. fracture system was developed and was occupied by the fluorspar veins. It is possible that the northwestward-trending dike of quartz monzonite three-quarters of a mile south of the stock was an important factor in the localization of this line of weakness. A roughly triangular block, bounded by the N. 40° W. fracture zone on the southwest, the stock on the north, and the northward- and northeastward-trending fluorspar veins on the southeast, was slightly pushed up and tilted, the edge next to the stock moving up more than the southern edge. Such an upward tilting would be expected to result from a force acting upward to the northeast, such as would have accompanied the emplacement of the magma. As would be expected, the greatest amount of brecciation occurred at the junction of the N. 70° W. breccia zone and the N. 40° W. fracture zone, on the west border of the stock. As the rock was all granite and maintained openings, the greatest amount of fluorspar was deposited there.

The brecciation of some of the fluorspar in the breccia zones indicates that further movement occurred after the deposition of the bulk of the fluorspar. This movement can be accounted for by a readjustment due to withdrawal of material from below and to cooling of the porphyry mass. These later openings were filled by the lead-silver ores and small amounts of later fluorspar.

It seems probable that the groups of northeastward-trending fractures on the northwest and east sides of the stock also resulted from the intrusion. As their upthrown sides, which also moved northeast, are nearest the stock, it is reasonable to infer that they resulted from a shearing component of the upward northeasterly push of the magma in the final stage of emplacement.

Origin of the Late Ore Fissures.—To complete the structural picture of the Jamestown district, it is necessary to account for the formation of the northeastward-trending fissures occupied by the pyritic gold veins and the gold-telluride veins. As above described, numerous fissures of northeasterly trend were opened during the intrusion of the stocks, but these were probably all filled by dikes or closed before the solutions that deposited the pyritic gold and gold telluride ores were introduced. However, these early faults were probably the controlling factor in the localization of the late ore fissures.

The major folding and faulting in the Front Range was brought to a climax by the intrusion of the porphyry stocks, but in some places residual regional stresses produced minor fracturing even after the intrusives had solidified. In the region just west and northwest of Boulder (Fig. 1) late compressive stresses of this type caused a slight westerly movement of a triangular block bounded by the foothills on the east, the east-west tungsten belt on the south, and the Jamestown district on the northwest. In the Jamestown district this late movement served to reopen many of the old northeastward-trending fissures and to produce some new ones; these were filled by pyritic gold veins and gold-telluride veins during the later stages of mineralization.

SUMMARY AND CONCLUSIONS.

The ore deposits of the Jamestown district are structurally and genetically related to the compound Tertiary intrusives of granodiorite and quartz monzonite. They are most closely related to the quartz monzonite stock and are grouped around it in a roughly zonal arrangement.

The linear structural features in the Tertiary stocks and dikes all pitch to the southwest, indicating that all these intrusives are derived from approximately the same source.

The irregular distribution of the ores is dependent on the distribution of the fractures, and these have apparently resulted in large part from stresses developed by the intrusion of Tertiary magmas. The strong fractures of northeast trend, although influenced by pre-Cambrian structure, have resulted chiefly from stresses developed by the emplacement of the granodiorite stock.

The breccia zones and fault fissures of northwest trend have resulted from stresses developed by the emplacement of the small quartz-monzonite stock. The emplacement of these stocks as worked out by the Cloos method seems to account adequately for the structural sequence of ore fissures in the district, and although regional compression played a small part in their formation, it falls far short of explaining the whole structural picture. Thus the Jamestown district affords a striking example of the value of mapping internal structural features of igneous masses related to ore deposits, as an aid in the attempt to solve the structural problems of ore distribution.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
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THE NEW HAMPSHIRE GARNET DEPOSITS.

LOUIS C. CONANT.

INTRODUCTION.

SINCE 1910 an almost continuous production of abrasive garnet has been maintained from New Hampshire where rocks containing about 50 per cent. almandite garnet ($Fe_3Al_2(SiO_4)_3$) occur near North Wilmot, in the northern part of Merrimack County. Smaller deposits in the adjoining town of Danbury were worked for a while, and several unexploited occurrences in that part of the state have distinct economic possibilities.

Previous Work.—Little has been known concerning the occurrence or origin of the mineral at these localities. The first deposit was discovered sometime prior to 1909 and was described in 1911 by Bardwell [1] who discussed the extraction and milling but not the geology. In 1914 there was published [2] a summary of a report apparently submitted to the owners of the North Wilmot quarry by C. Palache and A. D. Little & Co., describing the occurrence of the garnet but saying nothing concerning its origin. In 1930 George W. White and Harold M. Mayo of New Hampshire University visited the quarry, collected samples, and made chemical analyses, but were unable to continue the study at that time and turned over their analyses to the present writer.

ASSOCIATED ROCKS.

All the rich garnet deposits occur within an area shown on the various geologic maps of the state as being underlain by porphyritic granite (recently termed by Billings [3] "Meredith granite")

[1] Bardwell, E. S.: Garnet Milling in New Hampshire. Eng. and Min. Jour., vol. 91, June 17, 1911, pp. 1209–1210.

[2] U. S. Geol. Survey, Min. Res., 1913, Pt. II, pp. 265–266, 1914.

[3] Billings, Marland: The Petrology of the North Conway Quadrangle in the White Mountains of New Hampshire. Proc. Amer. Acad. Arts and Sci., vol. 63, pp. 67–137, 1928. See p. 83.

although some of the rock so designated is a partially granitized schist much resembling the granite itself, and it is in this modified schist that most, if not all, of the garnet deposits are found.

Meredith (porphyritic) Granite.—The Meredith granite outcrops in several parts of the state (Fig. 1), the largest occurrence

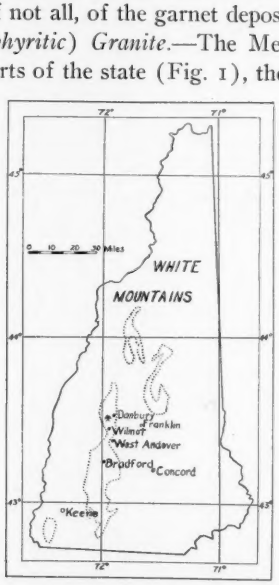

FIG. 1. Map of New Hampshire showing distribution of the largest areas (dotted lines) of the Meredith (porphyritic) granite, also location (pick and shovel) of the North Wilmot garnet quarry, and (heavy dots) other important garnet occurrences. Granite distribution after Hitchcock and Goldthwait.

being a batholith some 60 miles long and 5 to 12 miles wide. An area of similar rock occurs in central Massachusetts as a dike-like mass about 26 miles long and a third of a mile wide, called by Emerson [4] the Coys Hill granite. In New Hampshire the striking appearance of the rock has long attracted the attention of geologists. Whitney and Williams [5] described it as a "porphy-

[4] Emerson, B. K.: Geology of Old Hampshire County, Massachusetts. U. S. Geol. Surv. Mon. 29, p. 319, 1898. Also, Geology of Massachusetts and Rhode Island. U. S. Geol. Surv. Bull. 597, pp. 240–241, 1917.

[5] In C. T. Jackson's First Annual Report of the Geology of the State of New Hampshire, p. 50 (1841).

ritic granite " and regarded it as an igneous rock. Some 30 years later Hitchcock [6] stated his belief that it was a gneiss which had developed by the fusion of ancient sediments and that it was the foundation rock of New Hampshire stratigraphy. Such an interpretation might easily be reached by an examination of the granitized schists associated with it. In 1897 Daly [7] published the results of detailed studies along some of its contacts and demonstrated that the rock is a typical intrusion cutting the surrounding schists. In 1928 Billings [8] described its occurrence in the North Conway quadrangle and proposed the name Meredith granite.

The rock is light-colored and contains abundant phenocrysts of orthoclase feldspar typically 2 to 4 inches long and twinned according to the Carlsbad law. In the specimens studied during the present investigation, mostly from the largest area, the groundmass is chiefly of coarse-grained quartz, andesine feldspar, and biotite mica. Garnet, which is irregularly scattered through it, is present in various amounts up to 50 per cent. Under the microscope such accessory minerals as magnetite, zircon, rutile, and apatite are found; sillimanite and cordierite occur locally, some of the latter being abnormal in having an optically positive character. The orthoclase phenocrysts commonly show a pronounced alignment, probably the result of flowage while cooling.

Porphyritic Schist.—Much of the northern portion of the largest area mapped as granite is really granitized schist which has been so thoroughly soaked by granitic juices, with the accompanying development of feldspar phenocrysts, that except for a pronounced schistosity and an abnormally high biotite content, it now approaches the normal porphyritic granite in appearance. Three lines of evidence support this view:

1. There is such a gradation from almost unmistakable schist, through the porphyritic schist, to the normal porphyritic granite, that there can be little doubt that the feldspathic schist is the re-

[6] Hitchcock, C. H.: Geology of New Hampshire. 3 vols. and atlas, 1872–1878.

[7] Daly, R. A.: Studies on the So-Called Porphyritic Gneiss of New Hampshire. Jour. Geol., vol. 5, pp. 694–722, 776–794, 1897.

[8] *Op. cit.*, pp. 83–84.

sult of impregnation of the roof of the batholith by granitic material.

2. Bands of distinctly sedimentary appearance contain infiltrations of granitic magma, in the form of orthoclase phenocrysts, the growth of which has pushed aside the laminae, and in the form of quartz-andesine aggregates which occur as thin stringers and as rims around the phenocrysts. These features are best seen on the steep southeast slope of Ford Hill (southern edge of the Cardigan quadrangle). The summit and western portions of the hill show the porphyritic schist in close association with granite and abundant pegmatite.

3. Sillimanite-garnet schists closely associated with the granitized schist contain layers of quartzite a few inches thick.

The appearance of the rock conveys the erroneous idea that it has been crushed. The orthoclase phenocrysts are lenticular in outline and enclosed by rims about 1 mm. thick, which are suggestive of crushed borders but which the microscope reveals to be fine-grained quartz and andesine. In places the quartz-andesine stringers previously mentioned swell to a lenticular shape and strongly resemble crushed and drawn-out feldspars. Except for an undulatory extinction in the quartz, however, the minerals show little evidence of having been sheared or strained.

Other Rocks.—Pegmatite is abundant in the vicinity of the garnet deposits, several occurrences having been either worked or prospected for their mica, feldspar, or beryl content. A trap dike is exposed in the North Wilmot garnet quarry, although its presence there is thought to be only a coincidence, since such dikes are found in many parts of the state.

Age of the Rocks.—It is probable that the schists are northward extensions of somewhat similar ones in central Massachusetts which have been mapped by Emerson [9] as late Paleozoic. Recent work by Billings [10] has definitely established a Paleozoic age for many of the schists in central New Hampshire, and there

[9] Emerson, B. K.: Geology of Massachusetts and Rhode Island. U. S. Geol. Surv. Bull. 597, pp. 48–49, and accompanying map, 1917.

[10] Billings, M.: Paleozoic Age of the Rocks of Central New Hampshire. Science, vol. 79, pp. 55–56, 1934.

is at present no reason for believing those in the garnet area to be older. The Meredith granite was intruded subsequent to, or during the close of, the last major tectonic disturbance of the region, and is probably of late Paleozoic age.

CHARACTER OF THE GARNET DEPOSITS.

General.—In most of the more promising deposits the garnet rock is a massive aggregate averaging about 50 per cent. garnet, with a range of 30 to 80 per cent. In size the garnets are typically between an eighth and a half-inch in diameter, though the range is from microscopic dimensions to nearly an inch.

The deposits whose outlines are known are distinctly elongated parallel to the schistosity of the enclosing rock, which strikes about N. 20° E., and dips steeply to the east. They are generally from one hundred to several hundred feet in length and from a few feet to a hundred feet in width. Vertically they have not been traced downward more than 30 feet, although they doubtless continue much deeper.

Petrology.—The minerals associated with the garnet are chiefly quartz, biotite, magnetite, and sillimanite, with minor amounts of feldspar and chlorite and abundant tiny grains of zircon and rutile. The garnet contains numerous inclusions—one of the chief problems in the milling. For the most part these consist of minute grains of magnetite, biotite, and quartz, the first commonly showing a zonal arrangement parallel to the crystal edges (Fig. 2). The garnet is strongly fractured, and thin sheets of chlorite have developed as an alteration product in many of the cracks. No other mineral changes appear to have taken place since the time of formation. That the biotite inclusions are not retrogressive alteration products of a much later date is evidenced by the fact that they contain well developed halos around included zircons, as does the biotite indigenous to the matrix of the garnet. Rare pyrrhotite-tourmaline veinlets are believed to be of a slightly later date and of no significance in connection with the origin of the garnet.

Paragenesis.—The biotite, sillimanite, magnetite, some of the

quartz, and perhaps a little of the feldspar, were probably present in the schists prior to the formation of the garnet, as all of them are found as inclusions in it. The biotite and sillimanite have been distinctly bent aside by the growing garnet, and some of the biotite has evidently been replaced by it. Most of the feldspar, much of the quartz, and perhaps some of the silica of the garnet are believed to have been derived from the granitic magma.

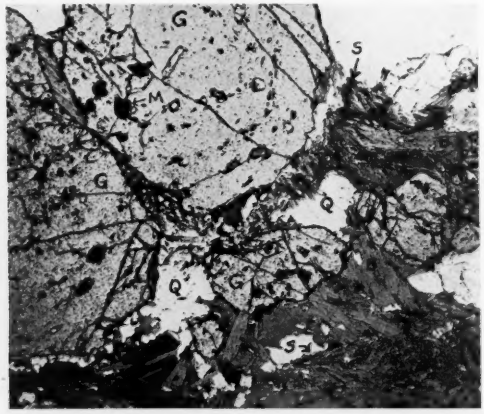

FIG. 2. Photomicrograph of garnet rock from North Wilmot quarry, showing garnet with typical inclusions. *G*, garnet; *M*, magnetite; *B*, biotite; *S*, sillimanite; *Q*, quartz. The sillimanite is intergrown with biotite, which here shows a uniform gray color. Ordinary light. ×7.

Physical and Chemical Properties of the Garnet.—The garnet occurs as dodecahedrons with trapezohedral combinations; but a rounded habit, resulting from the dodecahedron faces being built up of a series of successively smaller plates, tends to conceal the crystal forms.

The specific gravity is difficult to obtain with accuracy because of the numerous inclusions. Pycnometer determinations of crushed material which was examined under a hand lens for

the removal of more obvious impurities gave results ranging from 3.977 to 4.135.[10a]

The hardness is probably 7.5 or more, being somewhat in excess of that usually given for almandite garnet; Palache reports it to have a hardness of about 8.[11]

The fractures are typically parallel to the crystal edges and are thought to be manifestations of the poor dodecahedral parting or cleavage commonly attributed to the mineral.

The color is dark red, being most apparent in the fractured material.

Accurate chemical analyses also are out of the question, but two are published here, one for the first time.

TABLE I.

CHEMICAL ANALYSES OF WILMOT, N. H., GARNET.

	I [a]	II [b]
SiO_2	37.39	37.35
TiO_2	—	.79
Al_2O_3	20.46	20.36
Fe_2O_3	2.89	2.27
FeO	31.87	31.36
MnO	3.47	1.18
MgO	2.46	2.22
CaO	.92	2.55
Na_2O, K_2O	—	1.69
P_2O_5	—	.59
H_2O^+	—	.16
H_2O^-	—	.04
S	—	.36
NiO	—	.01
CuO	—	.05
	99.46	100.98

[10a] A similar variation was found by Myers and Anderson in a series of determinations of essentially clean garnet from two of the Adirondack localities (Garnet: Its Mining, Milling, and Utilization. U. S. Bur. Mines Bull. 256, pp. 40–41, 1925). It may be that pure garnet from the New Hampshire localities, if such were available, would show a like variation.

[11] Palache, C.: U. S. Geol. Surv., Min. Res. 1913, pt. II, p. 262, 1914.

[a] Myers, W. M., and Anderson, C. O.: *Op. cit.*, p. 38. Republished by Myers: The Mineralogy of Some Commercial Garnets. Amer. Jour. Sci. (V), vol. 12, pp. 115–118, 1926. Analyst, Marie Farnsworth.

[b] An analysis kindly made available by the analyst, Harold M. Mayo, of New

Myers attempted to recalculate the analyses of several commercial garnets, obtaining the following result for the Merrimack County material, from analysis I of the above table: [12]

Andradite	8.9%
Grossularite	0.0
Pyrope	10.0
Almandite	73.0
Spessartite	8.1
	100.0%

Considering the small amount of CaO in his analysis, the value 8.9 per cent. for andradite is much too high, since 0.92 per cent. CaO could only yield 2.8 per cent. andradite. He mentions the impurities in material from this locality, and it is clear that the analysis would not recalculate wholly into the various garnet molecules.

The writer has recalculated Mayo's analysis (II, Table I), making allowances for most of the probable impurities, and the following proportions were obtained: [13]

Rutile	.79%
Magnetite	3.29
Apatite	1.29
Orthoclase	9.98
Pyrope	7.28
Spessartite	2.75
Grossularite	4.95
Almandite	70.06
Andradite	0.00
	100.39%

Hampshire University. He writes that though the more obvious impurities were culled out, the material analyzed still "showed numerous inclusions of free quartz, magnetite, biotite, and apparently albite, pyrrhotite, and perhaps others." He also reports that a qualitative analysis of material from the same quarry showed the absence of ZrO_2, F, Cl, $(Ce, Y)_2O_3$ and several other oxides.

[12] Myers, W. M.: Amer. Jour. Sci., *Op. cit.*, p. 117.

[13] This result is admittedly inaccurate, since no attempt was made to compute biotite and quartz, both of which were probably present, and H_2O, NiO, CuO, and S were neglected. It is believed that this recalculation is about as accurate as can be obtained, although the amount of Al_2O_3 used is 0.52% less, and of SiO_2 0.65% more, than that available.

When the garnet molecules indicated above are recalculated to total 100 per cent., the result is as follows:

Almandite, $Fe_3Al_2(SiO_4)_3$	82.4%
Pyrope, $Mg_3Al_2(SiO_4)_3$	8.6
Grossularite, $Ca_3Al_2(SiO_4)_3$	5.8
Spessartite, $Mn_3Al_2(SiO_4)_3$	3.2
	100.0%

The commercial garnet of New Hampshire may thus be considered essentially almandite with only small percentages of pyrope, grossularite, and spessartite. If some of the MnO present was in the biotite or magnetite, as may well have been the case, the spessartite content would be even less than 3.2 per cent.

DESCRIPTION OF DEPOSITS.

North Wilmot.—The only extensively worked garnet deposit in the state, operated at present by Mr. Norman Davenport under the name of the Garnet Products Company, is located near the top of the hill just west of the North Wilmot school, and close to the southern edge of the Cardigan quadrangle. The opening, which is understood to be considerably larger than the original showing, is about 100 by 180 feet, and has reached a depth of 30 feet. When idle it is about half filled with water. The deposit probably strikes about N. 20° E. and dips steeply to the east, although there are no distinct boundaries to the mass as now exposed, and these statements are based on the strike and dip of the enclosing rock. Such an assumption of parallelism is probably justified, inasmuch as all the other deposits show similar relationships with the surrounding rock.

The hanging-wall rock is a well banded phase of the porphyritic Meredith granite, its contact with the garnet being irregular and gradational. The footwall of mica schist passes, a few feet westward, into a distinctly porphyritic schist rich in biotite and lenticular feldspar phenocrysts. Nearly vertical dikes of trap and pegmatite striking about N. 15° E. cut through the center of the de-

posit. Neither of these appears to have had any influence on the development of the garnet. Specimens found on the dump show pyrrhotite-tourmaline veinlets which likewise had no influence on the formation of the garnet. Two sillimanite-rich quartzitic bands, about 2 inches thick, occur in the northern part of the quarry and are thought to be remnants of original sedimentary layers. Occasional scattered patches of barren rock from a few inches to two or three feet in diameter are found in the midst of the garnet and are chiefly of a quartz-andesine-biotite composition, probably of igneous source. Many minor slip planes in the quarry cut through the garnet crystals and are coated with thin films of chlorite, which is probably an alteration product of garnet and biotite. Garnet forms about 50 per cent. of the rock; other prominent minerals are biotite, quartz, and feldspar.

A promising outcrop of garnet, the mining rights of which are owned by the Garnet Products Company, is located about two-thirds of a mile southeast of this quarry, on the southern edge of the Cardigan quadrangle, just east of the road leading south from near the North Wilmot school, and about 100 yards north of its lowest point. The rock has a variable strike which averages a little east of north, and is exposed for some 50 feet across the strike and about 60 feet along it, both ends being concealed by soil. Examination of the locality reveals the presence of granitic and pegmatitic material as well as the porphyritic schist, and it is apparent that the garnet is located close to the contact between the metamorphosed schist and the intruded material.

Danbury.—Rich garnet rock outcrops in several places on both sides of Severance Hill. On the east side three small openings were made during the years 1928–30, and a few thousand tons of quarried material was shipped to Dearborn, Michigan, where it was milled and used by the Ford Motor Company for polishing plate glass. Since 1930 there has been no activity at these quarries and, judging by the amount and quality of material in sight, it seems unlikely that they could compete successfully with the North Wilmot deposits or those to be mentioned below. The garnet occurs in distinct bands of variable widths between others

of porphyritic granite, porphyritic schist, granite, and mica schist. The strike is about N. 20° E. and the dips are easterly at various steep angles. One three-inch band of granite in the lowest opening is found on microscopic examination to contain many small bundles of sillimanite, probably representing a granitized sillimanitic layer. The whole assemblage in the quarries is strongly suggestive of partial granitization of the schist. A pocket of pyrrhotite and tourmaline was found in one of the openings during the quarrying, but these minerals are believed, as in the case of the North Wilmot quarry, to have been introduced after the formation of the garnet.

Deposits on the west side of Severance Hill are similar to the ones on the east side, except that they appear to be more extensive and richer, and have never been worked.

Other Deposits.—Many boulders and possibly an outcrop of rich garnet rock occur on the property of Henry Pilisbury, near West Andover.

Two other distinctly promising occurrences that may ultimately be of importance are known, but their locations cannot be given. One is reported to be in Bradford, but those who know its location refuse to divulge it. Specimens from there, claimed to be typical of a large deposit, contain about 80 per cent. garnet and are the richest material of its kind known to the writer. The other deposit was shown him confidentially and appears to be sufficiently rich and extensive to rank it among the more important occurrences of the mineral.

ORIGIN OF THE GARNET DEPOSITS.

Summary of Characteristics.—Wherever the geologic relationships are visible, the garnet rock is found to occur in the porphyritic schist close to the contact with the Meredith granite. The schist is apparently of sedimentary origin, has been soaked by granitic juices, and is bordered on the east by sillimanite-garnet schist containing layers of quartzite. Sillimanite is a common associate of the garnet, and sillimanite-rich rocks occur in both the North Wilmot and the Danbury quarries, the only places

where detailed studies can be made. Most of the garnet deposits are elongated parallel to the strike of the schist, and several of them are approximately in alignment.

Origin.—The garnet rock is thought to be the result of contact-metamorphic alteration of certain iron- and aluminum-rich portions of sedimentary rocks that had been previously dynamically metamorphosed. There is abundant evidence that the schists have been impregnated by igneous material and that the garnet has developed subsequent to the formation of the biotite and sillimanite, as has been the case with the orthoclase phenocrysts and the quartz-andesine stringers in the adjacent schists. The supposed sequence of events in the region is as follows:

1. Deposition of a series of Paleozoic sediments, certain layers or lenses of which were rich in iron and aluminum.

2. Dynamic regional metamorphism of the sediments with the production of biotite-sillimanite—possibly garnetiferous—schists from the iron-aluminum portions.

3. Intrusion of the porphyritic Meredith granite near the close of the Paleozoic, emanations from it penetrating and profoundly altering the roof and converting the iron-aluminum portions into the garnet-rich rock.

4. Introduction of pegmatite and veins of pyrrhotite and tourmaline during the closing stages of magmatic activity.

5. Intrusion of trap rock, possibly contemporaneously with the Triassic eruptions of similar near-by material in Massachusetts and Connecticut.

6. Subsequent period of little disturbance while weathering and erosion removed sufficient material to expose the top of the batholith and its overlying contact aureole, one phase of which is the garnet rock.

The discontinuous nature of the deposits is thought to be due to original unevenness in the distribution of material of suitable composition for the formation of the garnet, although it may be the result of irregularities in the igneous emissions. It is possible, however, that the garnet rock is more continuous than present evidence indicates. The failure of all the deposits to be

aligned as though in one sedimentary bed may be explained by postulating isoclinal folding, faulting, or the existence of original iron-aluminum-rich lenses at more than one sedimentary horizon.

OUTLOOK FOR THE GARNET INDUSTRY IN NEW HAMPSHIRE.

There is no apparent reason why the state should not maintain its place second to New York as the chief producer of abrasive garnet for years to come, or even take the lead if New York deposits should become exhausted. Five localities other than the one at present being worked show distinct promise, namely: (1) the North Wilmot reserve; (2) those on the west side of Severance hill, Danbury; (3) the West Andover deposit; (4) and (5) the two deposits whose locations cannot at present be given, including a remarkably rich one supposed to exist somewhere in Bradford. Many other rich deposits doubtless occur beneath the nearly continuous cover of glacial drift, and it would be a coincidence indeed if the first one found and worked proved to be the richest and largest.

Further discoveries are likely to be either by accidental uncovering during the construction of buildings or highways, or by geophysical methods. Since the rock is rich in magnetite, as well as biotite and garnet, magnetometer surveys might prove useful in tracing the continuations of known deposits and possibly in locating new ones, providing, of course, that the associated rocks do not contain an equal amount of magnetic minerals. It is not believed that any geophysical experiments have been conducted on these rocks.

ACKNOWLEDGMENTS.

Mr. Norman Davenport has permitted unlimited examinations of his properties and has contributed much valuable information. Dr. George W. White and Mr. Harold M. Mayo have generously placed their findings at the writer's disposal. Drs. H. Ries, E. B. Mayo and J. D. Burfoot Jr. have offered many helpful criticisms and suggestions during the course of the work.

CORNELL UNIVERSITY,
ITHACA, N. Y.,
Aug. 27, 1934.

HYDROTHERMAL EXPERIMENTS WITH GOLD.

STEPHEN P. OGRYZLO.

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INTRODUCTION.

THE solution and transportation of gold in nature has been the subject of much discussion. This investigation of gold and some of its compounds was, therefore, undertaken in order to throw further light on the manner in which gold is dissolved and transported by hot solutions and gases. To date, little detailed information is available on the solvent action of various substances on gold under high temperature and pressure conditions.

It is generally believed that gold is carried in solution as a chloride, because of the stability of gold chloride as compared with the other compounds of gold. It is probable that gold, in some instances, has been carried in the vapor state, also as a chloride. Goodchild[1] has reported a case where gold found around a volcanic cone was probably brought up in the vapor state. Gold is easily brought into the colloidal state and as such

[1] Goodchild, W. H.: The Evolution of Ore Deposits from Igneous Magmas. Mining Mag., vol. 19, p. 191, 1918.

it is believed by some to be transported in solutions of colloidal silica. Colloidal gold, however, is readily precipitated by electrolytes and, therefore, it is not likely that it is transported in this form to any great extent.

This problem was proposed by Dr. J. W. Gruner, who throughout the investigation has very generously given valuable suggestions and assistance. Grateful acknowledgment is due to Dr. R. B. Ellestad, who contributed valuable advice and suggestions, also to the Graduate School of the University of Minnesota, which made possible the acquisition of equipment for this work.

PREVIOUS WORK.

Of the experimental work carried out on the solution and transportation of gold, that of Stokes [2] is probably the most suggestive. Stokes dissolved gold leaf in the absence of air, in hydrochloric acid solutions of cupric chloride and of ferric chloride, at 200° C. Upon cooling, metallic gold was redeposited. Not a trace of gold was dissolved by a ferric sulphate solution after heating for 52 hours at 200° C., which disproved Wurtz's [3] statement that gold dissolves in ferric sulphate.

McCaughey [4] was able to dissolve gold in hydrochloric acid solutions of ferric sulphate and cupric chloride at 38° C. Upon cooling, the solution of ferric sulphate deposited fine spangles of gold. It appears, therefore, that ferric sulphate will dissolve gold only in the presence of a chloride. McCaughey [5] also found that gold is soluble in ferric sulphate in the presence of ferrous salts, but the solvent action decreases with increase in concentration of the ferrous salt. He states that the amount of gold dissolved in cupric chloride and ferric chloride solutions increases more with the concentration of the acid than with an increase in concentration of the salt, especially in the case of the copper salt.

[2] Stokes, H. N.: Experiments on the Solution, Transportation and Deposition of Copper, Gold, and Silver. ECON. GEOL., vol. 1, pp. 649–650, 1905–06.

[3] Wurtz, H.: Contributions to Analytical Chemistry. Amer. Jour. Sci., (2) vol. 26, p. 51, 1858.

[4] McCaughey, W. J.: The Solvent Effect of Ferric and Cupric Salt Solutions upon Gold. Jour. Amer. Chem. Soc., vol. 31. p. 1267, 1909.

[5] *Idem.*, p. 1269.

McIlhiney [6] also investigated the solubility of gold in ferric chloride and in hydrochloric acid in closed tubes. He concludes that hydrochloric acid in the presence of air is without solvent action on metallic gold and that ferric chloride is without action on gold unless oxygen is present. These results do not agree with those of Stokes, who was able to dissolve gold in a hydrochloric acid solution of ferric chloride in the presence of carbon dioxide. Lenher [7] found that lead oxide facilitates the solution of gold when added to solutions of ferric sulphate and sodium chloride.

Little experimental work has been done on the solubility of gold in hydrochloric acid under pressure. McCaughey [8] failed to dissolve gold in boiling concentrated hydrochloric acid. Lenher,[9] in his investigation on the solubility of gold, was able to dissolve gold in concentrated hydrochloric acid under pressure. He also found that alkaline chlorides, such as sodium, potassium, and ammonium chlorides, in solution with hydrochloric acid and also aqueous solutions of the above-mentioned chlorides, will cause gold leaf to pass into solution when heated in a sealed tube under pressure. The pressures obtained in the experiments were all below 100 pounds per square inch and the temperatures ranged to 165° C. Morris [10] found that magnesium chloride solution at 260°–270° C. exerted no solvent action on gold leaf.

Alkaline solutions such as the alkaline silicates or carbonates have given only uncertain results when heated under pressure with gold leaf. Doelter [11] claims that gold is perceptibly soluble in a 10 per cent. sodium carbonate solution, and also in a mixture of sodium bicarbonate and sodium silicate.

[6] McIlhiney, P. C.: The Action of Ferric Chloride on Metallic Gold. Amer. Jour. Sci., (4) vol. 2, p. 293, 1896.

[7] Lenher, V.: Solubility of Gold. Jour. Amer. Chem. Soc., vol. 26, p. 552 1904.

[8] McCaughey, W. J.: *Op. cit.*, p. 1263.

[9] Lenher, V.: Some Observations on Tellurides. ECON. GEOL., vol. 4, p. 562, 1909.

[10] Morris, H. H.: Chemistry of Gold. Jour. Amer. Chem. Soc., vol. 40, p. 921, 1918.

[11] Doelter, C.: Einige Versuche über die Löslichkeit der Mineralien. Min. pet. Mitt., vol. 11, p. 328, 1889–90.

Egleston [12] made some experiments with gold in sealed tubes at temperatures between 145° and 180° C. He found that no gold was dissolved by magnesium chloride, sodium sulphate, or commercial sulphuric acid and solutions of potassium, iron, and manganese sulphates. Also, solutions of sodium sulphate and sodium nitrate dissolved no gold. Lenher [13] found that gold would dissolve in concentrated sulphuric acid or strong phosphoric acid in the presence of oxidizing agents, such as manganese dioxide.

Egleston,[14] in studying the formation of gold nuggets in placer deposits, found spongy gold to be dissolved in alkaline sulphides when heated in glass tubes for 6½ hours between 145° and 180° C. Green solutions were obtained which, according to his statement, reacted for gold. Becker,[15] in his studies on the mercury deposits of the Pacific coast, was able to dissolve gold dust in sodium sulphide at room temperature and pressure. Lenher [16] repeated some of these experiments, and states that he was able to get the gold into solution. He gives no details of the experiments, however.

In 1888, Christy [17] published some very interesting results on the losses in the roasting of gold ores with salt and the volatility of gold in an atmosphere of chlorine. In passing a current of chlorine over gold, he found that the losses in the weight of the gold increase to a maximum at about 250° C. and then rapidly diminish to a minimum at a temperature somewhere below red heat. The chlorine was generated from pyrolusite and hydrochloric acid. In some of the experiments it was passed over the gold in a moist state; in others it was first bubbled through strong sulphuric acid to remove some of the moisture.

12 Egleston, T.: The Formation of Gold Nuggets in Nature. Trans. Amer. Inst. Min. Eng., vol. 97, p. 639, 1880–81.

13 Lenher, V.: *Op. cit.*, Jour. Amer. Chem. Soc., vol. 26, p. 550.

14 Egleston, T.: *Op. Cit.*, p. 640.

15 Becker, G. F.: Natural Solutions of Cinnabar, Gold, and Associated Sulphides. Amer. Jour. Sci., (3) vol. 33, p. 209, 1887.

16 Lenher, V.: The Transportation and Deposition of Gold in Nature. Econ. Geol., vol. 7, p. 746, 1912.

17 Christy, S. B.: The Losses in Roasting Gold Ores, and the Volatility of Gold. Trans. Amer. Inst. Min. Eng., vol. 17, pp. 3–45, 1888–89.

Rose[18] obtained somewhat similar results on passing dry chlorine over gold. He found that the maximum volatilization takes place at 288° C., the melting point of the auric chloride. The volatilization then rapidly decreases to a minimum at about 750° C., and again increases above 800° C.

EXPERIMENTS.

The experiments in connection with this problem were made in three types of apparatus. The dynamic experiments were made in a tube furnace, and the high temperature and pressure experiments were performed in gold-lined bombs and pyrex tubes.[19]

Two groups of experiments were made. The first group deals

[18] Rose, T. K.: The Dissociation of the Chloride of Gold. Jour. Chem. Soc., vol. 67, p. 899, 1895.

[19] The tube furnace used was similar to the one used by Dr. J. W. Gruner. (Hydrothermal Oxidation and Leaching Experiments. ECON. GEOL., vol. 25, p. 707, 1930.) It consists of an alundum core around which nichrome wire is wound. A wide pyrex tube was passed through the alundum core. One end of the pyrex tube was connected to a three-liter flask in which steam or HCl vapor and steam was generated on a hot plate. The other end was connected to a condenser by means of a ground-glass stopper. In order that the vapors could be generated continuously, another three-liter flask was connected to the generating flask by a siphon arrangement and in this way the water or hydrochloric acid in the generating flask did not stop boiling during the interval of the experiment. The gold sheet over which the vapors passed was placed in either a porcelain boat or a crucible in the pyrex tubing near the end of the thermocouple. A Hoskins chromel-alumel thermocouple was used to record the temperature. The variation in the temperature was 10° ±.

The bombs used in the high temperature and pressure experiments were of 50 cc. capacity and were lined with 24-carat gold. In all the bomb experiments 25 cc. of solution was used. The space above the solution in the bomb was filled with air, carbon dioxide, or nitrogen. When carbon dioxide or nitrogen was used, these gases were allowed to displace all the air before the bomb was sealed. This was done by projecting a long drawn-out glass tube into the bomb, partially covering the open end with a gold sheet used for sealing the bomb, and allowing the gases to pass in with considerable velocity for several minutes. The bomb was immediately sealed with a 24-carat gold sheet, and placed in an electric furnace with a temperature control attached to it. There was a variation of 3° ± in the temperature.

The pyrex tubes used in some of the experiments were about 14 inches long, with an outside diameter of 3/4 inch and an inside diameter of 7/16 inch. About 20 cc. of solution was used. The gold was put into the tube, the tube sealed and the solution introduced into the tube through one of the capillaries. The air in the tube was displaced by either carbon dioxide or nitrogen, and the capillaries were then sealed off.

with the action of HCl vapor and chlorine gas in the presence of steam on gold; the second group, with the solvent action of various substances on gold under high temperature and pressure conditions. The details of the experiments, together with the results, will be given in subsequent tables.

Annealed gold sheet was used in all the experiments except those made in 24-carat gold-lined bombs. The gold sheet was well washed in hot concentrated hydrochloric acid and then dried and carefully weighed; any loss of gold was detected by weighing. In the case of the bomb experiments no gold was introduced into the bomb, as it was lined with gold. The bomb was well washed and burnished before each experiment and was placed in the furnace in an inverted position. The gold sheet used for sealing the bomb was examined with a binocular microscope after the experiments, for etching and depositions of gold. From one-half hour to 2 hours was allowed for the cooling of the bombs and pyrex tubes at the end of the experiments. The distilled water used for making up solutions was first boiled for about ten minutes to expel any air that may have been dissolved in it. The gold dissolved by the solutions was precipitated, and the amount determined if it was present in measurable quantities. Solutions that appeared to contain little or no gold in solution were tested with stannous chloride.[20]

The chlorine gas used in some of the experiments was obtained in cylinders and was first bubbled through water so that the

[20] Solutions that were colorless after the experiment and contained no alkali sulphides were evaporated to about one-tenth of their volume and tested for gold with a mixture of stannous and stannic chlorides. This is a very sensitive test, it being possible to detect one part of gold in 100,000,000 parts of water when a Nessler's tube is used. A purple coloration in the solution indicates the presence of gold.

The purple-of-Cassius test could not be used on solutions that contained alkali sulphides. It was first necessary to decompose the sulphide with hydrochloric acid. The solution was then evaporated to dryness, and aqua regia was added to dissolve any gold that might have been precipitated. This was again evaporated to dryness and some water was added to dissolve the gold chloride that was formed. The solution was then tested for gold with stannous chloride.

In the case of solutions which contained weighable quantities of gold, the gold was first converted to gold chloride, if it was not originally present in solution in that form, and then precipitated with sodium sulphite.

strength of the current would be known approximately. The chlorine was passed over the gold in a slow stream together with the steam. The strength of the current was kept constant as far as possible. At the end of the experiment the chlorine was shut off and the water was allowed to boil for a few minutes to expel most of the chlorine from the furnace.

Dynamic Experiments with HCl Vapor and Steam.

A number of experiments were made in a tube furnace by passing 20-per cent. hydrochloric acid vapor over annealed 24-carat gold sheet. The results are given in Table I. It was

TABLE I.

DYNAMIC EXPERIMENTS WITH 20 PER CENT. HYDROCHLORIC ACID VAPOR.

No.	Material	Hours	Temp. °C.	Results
1.	1.4290 gms. Au	21½	400	Weight unchanged
2.	1.4290 gms. Au	57	500	Weight unchanged
3.	1.4290 gms. Au	40	600	Weight unchanged
58.	0.7084 gm. Au	55	250	Weight unchanged
71.	0.6527 gm. Au, $FeCl_3.6H_2O$*	49	200	Loss of 0.0011 gm. in weight of Au. Most of $FeCl_3$ volatilized. Remainder changed to Fe_2O_3
59.	0.7083 gm. Au, $FeCl_3.6H_2O$*	61	250	Weight of gold unchanged. $FeCl_3$ changed to Fe_2O_3

* $FeCl_3$ placed in a separate boat in front of the boat containing the gold.

thought that HCl vapor would attack the gold, and form auric chloride, which would be volatilized in part. Experiments were made at temperatures of 250°, 400°, 500°, and 600° C., and were continued on the average for about 40 hours. No losses occurred in the weight of the gold that were not within the limits of experimental error.

Auric chloride ($AuCl_3$) would form and volatilize if pressure could be applied in the dynamic system, for, as will be shown later, gold chloride is formed when weak hydrochloric acid and gold are heated in a bomb.

Experiments were made in a tube furnace at 200° and 250° C. with a boat containing ferric chloride placed in front of a boat

containing gold. Ferric chloride dissociates slightly, around 250° C., into ferrous chloride and chlorine. The partial pressure of Cl_2 at 291° C. is 24.1 mm. Hg.[21] It was thought that by introducing ferric chloride into the dynamic system together with the gold, the chlorine liberated by the dissociation of ferric chloride would act upon the gold to form $AuCl_3$. This would result in a loss in the weight of the gold, for at these temperatures $AuCl_3$ is volatile to a certain extent. The steam and HCl vapor passed first over the ferric chloride, and then over the gold. At the end of the experiments some ferric oxide was present in the boat placed at the front, but most of the ferric chloride had volatilized. No significant loss in the weight of the gold occurred.

Dynamic Experiments with Chlorine and Steam.

$AuCl_3$ dissociates very slowly below 100° C., and more rapidly at high temperatures, with the formation of AuCl and chlorine.[22] Aurous chloride (AuCl) also decomposes gradually into gold and chlorine at 185° C., and more rapidly at higher temperatures.[23] The following equations express the reactions:

$$AuCl_3 \rightarrow AuCl + Cl_2$$
$$2AuCl \rightarrow 2Au + Cl_2.$$

According to Petit, the dissociation pressure of $AuCl_3$ at 100° C. is 5.8 mm. Hg. This increases rapidly, until at 251° C. it is 784.1 mm. (Fig. 1).

Despite the fact that $AuCl_3$ dissociates so rapidly, it can be easily sublimed at certain temperatures, due to the fact that its vapor pressure also increases rapidly. The latter, however, increases less rapidly than the dissociation pressure. Petit found that the vapor pressure of $AuCl_3$ increases gradually from 1.2 mm. at 100° C. to 67 mm. at 326° C. (Fig. 1).

[21] Maier, C. G.: Vapor Pressures of the Common Metallic Chlorides and a Static Method for High Temperatures. U. S. Bur. Mines, Tech. Paper 360, p. 53, 1925.

[22] Petit, M.: Sur la Dissociation du Chlorure Aurique. Bull. de la Soc. Chemique de France, (4) vol. 37, pp. 615–623, 1925.

[23] Roscoe, H. E., and Schlorlemmer, C.: A Treatise on Chemistry, p. 513. Macmillan, London, 1913.

It will be seen that above 200° C. the dissociation pressure increases much more rapidly than the vapor pressure. The rise in vapor pressure tends to increase, and that of the pressure of dissociation tends to reduce, the amount of gold volatilized as chloride.

Gold and chlorine unite at ordinary temperature in the presence of moisture.[24] Rose says that the rate of action increases to a

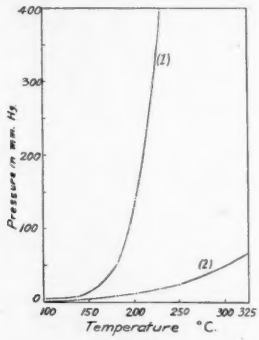


FIG. 1. (1) Dissociation pressure curve of $AuCl_3$. (2) Vapor pressure curve of $AuCl_3$. (Data after Petit.)

maximum at 225° C. and diminishes at higher temperatures. It was thought that by passing chlorine and steam over gold, conditions existing in nature could be reproduced to a certain extent and some idea would be obtained as to the transfer of gold in the vapor phase. A series of experiments were made at different temperatures between 125° and 500° C. Chlorine gas at atmospheric pressure was introduced into the furnace, together with the steam, at the rate of 1.5 to 2 liters per hour. About three liters of water was used every 24 hours for generating the steam. It was found that below 175° C. the $AuCl_3$ that was formed had a tendency to creep over the sides of the boat, and therefore a porcelain crucible was used. As the strength of the chlorine cur-

[24] Rose, T. K.: The Precious Metals Comprising Gold, Silver, and Platinum, p. 20. D. Van Nostrand Co., 1913.

rent has an effect on the amount of $AuCl_3$ volatilized, the chlorine stream was, as far as possible, maintained constant in all the experiments. An effort was also made to keep a constant area of gold surface exposed in the different experiments. There was a variation of 10° C. ± in the temperature.

The gold chlorides that formed on the gold sheet were converted to gold to determine the loss in the weight of the gold due to volatilization of $AuCl_3$.[25] As the experiments were not all continued for the same length of time, the losses in the weight of the gold were calculated for an interval of 33 hours. This would result in a small error, especially in the case of the experiments run for less than 33 hours, as a short time would be required for some gold chloride to form at the beginning of the experiment.

TABLE II.

DYNAMIC EXPERIMENTS WITH CHLORINE AND STEAM.

No.	Orig. wt. of Au in gms.	Temp. ° C.	Hours	Loss in gms.	Loss calc'd for 33 hrs.	% Loss for 33 hrs.	Remarks
81.	0.6365	125	22	0.0124	0.0186	2.92	Most of Au converted to $AuCl_3 2H_2O$. Some AuCl also formed
67.	0.6968	125	33	0.0258	0.0258	3.72	
79.	0.7054	150	33	0.0272	0.0272	3.86	
83.	0.6097	175	14	0.0129	0.0304	4.99*	Gold sheet covered with anhyd. $AuCl_3$ xls. Some AuCl also present
62.	0.6252	175	34½	0.0503	0.0484	7.74	
60.	0.7069	200	34	0.0695	0.0674	9.54	Gold sheet covered with a layer of anhyd. $AuCl_3$ xls.
54.	0.7824	200	33	0.0736	0.0736	9.41	Some AuCl also formed
61.	0.6471	225	33	0.0119	0.0119	1.84	Gold sheet only partly covered with anhyd. $AuCl_3$
50.	0.8101	250	49	0.0161	0.0108	1.33	
52.	0.7940	300	50½	0.0094	0.0061	0.77	Only a small amount of anhyd.
53.	0.7846	350	48	0.0022	0.0015	0.19	$AuCl_3$ present on gold sheet
44.	0.7798	450	58	0.0002	—	—	No $AuCl_3$ present
43.	0.7809	500	61	0.0011	0.0006	0.08	No $AuCl_3$ present

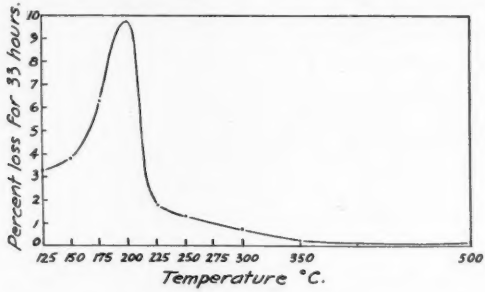
* Due to an unforeseen interruption in the heating current during this experiment the result is questionable.

It will be seen from the results in Table II, and from Fig. 2, that the volatilization of $AuCl_3$ in the presence of chlorine and

[25] If the $AuCl_3$ was anhydrous, the crucible was heated in a bunsen flame to decompose the $AuCl_3$ and AuCl on the gold sheet. A small amount of $AuCl_3$ volatilized during the heating. As this would result in only a small error, no allowance was made for it in the results. When the $AuCl_3$ was hydrous, it was taken into solution and the gold precipitated with sodium sulphite.

steam begins even below 125° C., for it was found that at that temperature about 3 per cent. of the gold by weight had volatilized as $AuCl_3$. The amount rapidly increases to a maximum at 200° C., where it is about 9.5 per cent., and then rapidly decreases to about 2 per cent. at 225° C., and to almost nothing at 400° C.[26]

The largest quantities of $AuCl_3$ were formed at 200° C. and



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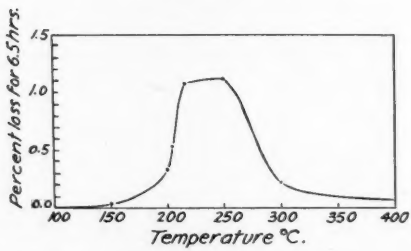

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FIG. 2. Curve for losses in weight of gold.
FIG. 3. Curve for losses in weight of gold. (Data after Christy.)

the surface of the gold sheet was completely covered with a layer of $AuCl_3$ crystals. In the experiments made above 200° C. the surface of the gold sheet was only partially covered with $AuCl_3$. The very sharp drop in the curve above 200° C. (Fig. 2) may, therefore, be partly due to the fact that the surface area of $AuCl_3$

[26] These percentage losses by weight give only relative results, as the amount volatilized is determined by the surface of the gold sheet rather than by its weight.

exposed rapidly decreased as the temperature was raised above 200° C.

Some of the gold chloride that was volatilized condensed on the pyrex tubing containing the thermocouple and also on the walls of the large pyrex glass tube near the end of the furnace.

Christy,[27] on passing chlorine over gold, found that volatilization begins around 100° C., increases to a maximum at about 250° C., then diminishes to a minimum somewhere below red heat, and again increases, but more slowly, to another maximum at a temperature above the melting heat, as shown in Fig. 3. Moist chlorine was used in most of these experiments.

Rose [28] reports that the greatest volatilization takes place at 288° C., the melting point of $AuCl_3$, when dry chlorine is passed over gold. He finds (Fig. 4) that volatilization begins around

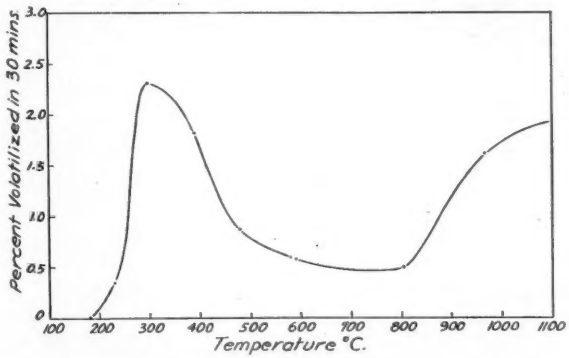

FIG. 4. Curve for the amount of gold volatilized. (After Rose.)

180° C., increases rapidly to a maximum at 288° C., then gradually decreases to a minimum around 800° C. and again increases.

It appears that water vapor has an effect on the point of maximum volatilization, for the writer found the maximum volatilization to be around 200° C. when chlorine and steam were passed over gold, whereas Christy, using moist chlorine, found that

[27] Christy, S. B.: *Op. cit.*, p. 25.

[28] Rose, T. K.: *Op. cit.*, Jour. Chem. Soc., vol. 67, p. 899.

maximum volatilization took place around 250° C., and Rose, using dry chlorine, found it to be around 288° C. It may be that when steam is present the chlorine is removed faster, thus decreasing the partial pressure of the chlorine and enabling dissociation to proceed more rapidly.

It is probable that if the partial pressure of the chlorine in the dynamic system were increased, the temperature at which maximum volatilization takes place would be raised, since the partial pressure would suppress to a certain degree the dissociation of the chloride.

Lenher [29] says that at high temperatures the pressure exerted by the expansion of steam greatly affects the decomposition of gold chloride. He found that when gold chloride was heated in a bomb there was no decomposition of the chloride until the critical temperature of the water was reached. The presence of alkali chlorides had a marked effect on the decomposition point. Lenher heated a gold chloride solution containing 10 per cent. $CaCl_2$ to 404° C. for nearly a day and did not obtain the slightest decomposition. Gold chloride containing 8 per cent. $CaCl_2$ was heated to 454° C. for a similar length of time, and in this experiment a few crystals of gold were obtained. A gold chloride solution containing 8 per cent. sodium chloride when heated to 460° C. showed no reduction to gold.

Christy [30] says that the gold is volatilized in a form not easily condensible. He was unable to condense the whole of the chloride by cooling alone. In order to recover the gold with any degree of efficiency, he found it necessary to remove the chlorine which carries the gold.

Metallurgists [31] also have found it difficult to condense gold chloride effectively from the vapor state when gold ores are roasted in a stream of gases with common salt. Bags, sprays, and solution towers were tried at the recovery end, but without success.

[29] Lenher, V.: Further Studies on the Deposition of Gold in Nature. ECON. GEOL., vol. 13, pp. 178, 183, 1918.

[30] Christy, S. B.: *Op. cit.*, p. 37.

[31] Parmelee, H. C.: The Volatilization Process in the Metallurgy of Gold. Met. & Chem. Eng., vol. 11, p. 230, 1913.

The occurrence of gold as a volcanic emanation has been reported by Goodchild.[32] The crater of the volcano La Sufral in Colombia is periodically filled by jets of steam from which sulphur is deposited. Numerous assays of the sulphur were made and it was found to contain from ¼ to 1 dwt. gold per ton. The gold was free and could be easily detected by panning. Hundreds of tests were also made of the thin soil in the neighborhood of the volcano, and it was found to contain from ¼ to 1 dwt. gold per ton.

High Temperature and Pressure Experiments.

With Hydrochloric Acid.—There appears to be some disagreement among investigators as to the solubility of gold in hydrochloric acid under pressure. Lenher[33] says that although hydrochloric acid under pressure dissolves gold, solution occurs only in concentrated acid; and hydrochloric acid, therefore, is of no importance as a natural solvent. McIlhiney[34] concludes, from experiments in sealed tubes at 150° C., that concentrated hydrochloric acid in the presence of air is without solvent action on metallic gold. However, experiments made by the writer with hydrochloric acid in a gold-lined bomb show that considerable amounts of gold are dissolved by comparatively weak hydrochloric acid in the presence of air (Table III). The reaction can be expressed by the following equation:

$$4Au + 12HCl + 3O_2 \rightarrow 4AuCl_3 + 6H_2O.$$

The amount of gold dissolved by hydrochloric acid depends on the concentration of the acid, the composition of the gases in the bomb, and the temperature and pressure at which the experiment is made. Time, of course, is also an important factor. Table IV gives the amounts of gold dissolved by different concentrations of acid at 300° C. in the presence of air, carbon dioxide, and nitrogen. From this table it will be seen that the amount of gold dissolved by hydrochloric acid increases considerably with the

[32] Goodchild, W. H.: *Op. cit.*, p. 191.

[33] Lenher, V.: *Op. cit.*, Econ. Geol., vol. 7, p. 745.

[34] McIlhiney, P. C.: *Op. cit.*, p. 293.

TABLE III.

HIGH TEMPERATURE AND PRESSURE EXPERIMENTS IN A *Gold-lined* BOMB WITH HYDROCHLORIC ACID.

No.	Material	Gas	Hours	Temp. ° C.	Pts. per mil. of Au dissolved	Results
5.	25 cc. .5N HCl	Air	59	300	1396	Solution yellow. 0.0349 gm. Au in solution
6.	25 cc. .05N HCl	Air	59	200		Solution colorless. Trace of Au in solution
8.	25 cc. .05N HCl	Air	50	300	412	Solution yellow. 0.0103 gm. Au in solution
9.	25 cc. .05N HCl	CO_2	50	300		Solution colorless. No gold in solution
41.	25 cc. .25N HCl	CO_2	$45\frac{1}{2}$	300		Solution colorless. Trace of Au in solution. Gold sheet etched in a few spots and some gold deposited on it
49.	25 cc. .5N HCl	CO_2	$42\frac{1}{2}$	300	312	Solution yellow. 0.0078 gm. Au in solution. Gold sheet considerably etched and some gold deposited on it
66.	25 cc. .5N HCl	CO_2	47	200		Solution colorless. Trace of Au in solution. Gold sheet very slightly etched
57.	25 cc. .5N HCl	N	43	300	92	Solution light yellow. 0.0023 gm. Au in solution. Gold sheet slightly etched. Little gold deposited on it
55.	25 cc. .1N HCl	N	48	300	940	Solution yellow. 0.0235 gold in solution. Gold sheet considerably etched. Some gold deposited on it

TABLE IV.

AMOUNTS OF GOLD DISSOLVED BY DIFFERENT CONCENTRATIONS OF HCl, USING AIR, CO_2, AND N AS ATMOSPHERES IN THE BOMB.

Temp. 300° C. (gold dissolved from the lining of the bomb)

Gas present in bomb	Air		CO_2		N	
Conc. of HCl	Gms. Au dissolved	Hours	Gms. Au dissolved	Hours	Gms. Au dissolved	Hours
.05N	0.0103	50	None	50		
.25N			Trace	$45\frac{1}{2}$		
.5N	0.0349	59	0.0078	$42\frac{1}{2}$	0.0023	43
1N					0.0235	48

concentration of the acid. Temperature and pressure have a very important effect on the solution of gold in hydrochloric acid. Of the two, pressure is probably the more important factor, for, as has already been shown, 20 per cent. HCl vapor had no action on gold between 250° and 600° C. at atmospheric pressure. Also, only a trace of gold was dissolved by 0.05N hydrochloric acid when heated at 200° C. for 59 hours, whereas, when acid of the same concentration was heated in a gold-lined bomb for 50 hours at 300° C., 0.0103 gram of gold was dissolved. In the latter experiment, the pressure developed by the water vapor was approximately 5 times that developed in the former.

In all the experiments where weighable amounts of gold were present in solution, the gold sheet used for sealing the bomb was greatly etched. Some gold probably precipitated out on cooling, since small mounds of gold were generally found deposited on the gold sheet.

With Chlorides and Sodium Carbonate.—A number of experiments were made to determine the solubility of gold in alkaline chlorides. The results are given in Table V. Lenher [35] says that the presence of alkaline chlorides such as sodium, potassium, or ammonium chlorides in solution with HCl will cause gold leaf to pass into solution when heated in sealed tubes under pressure. This of course would be expected, as it has been shown that dilute HCl alone will dissolve gold. His statement that aqueous solutions of the above-mentioned chlorides will also cause solution of gold seemed to need a check.

Experiments were made in a gold-lined bomb with approximately 0.7N and 2N NaCl solutions at 300° C. The solutions at the end of the experiments were colorless and gave a negative test for gold. However, when the solutions were evaporated to dryness, the sodium chloride in both cases had a purplish tint. It is probable that this coloration was due to colloidal gold, for when the sodium chloride was treated with aqua regia a test for a *trace* of gold was obtained. The gold sheet used for sealing the bomb was etched in a few places.

[35] Lenher, V.: *Op. cit.*, ECON. GEOL., vol. 4, p. 562.

A solution of ammonium chloride was made by dissolving 1 gram of NH_4Cl in 25 cc. of water. When it was heated at 200° C. for 35 hours in a gold-lined bomb it dissolved no gold and the gold sheet was not etched.

An experiment was made with an approximately 10 per cent. solution of Na_2CO_3 and gold sheet in a closed tube at 200° C. At the end of 46½ hours much silica but no gold was found in solution. Doelter [36] reports an experiment showing that at the end of 47 days, 1.22 per cent. of gold was lost when it was heated with a 10 per cent. solution of Na_2CO_3 in a closed tube at 200°–250° C. It is difficult to see how gold could be dissolved by Na_2CO_3, as there is no carbonate compound of gold. Also, it may be pointed out that gold crucibles are often used for making sodium carbonate fusions because of the fact that they are not corroded by the carbonate.

Stokes [37] found that ferric chloride in solution with HCl would cause solution of gold. This experiment was repeated by the writer, and results similar to those of Stokes were obtained. A solution made up of 1 gram of $FeCl_3.6H_2O$ and 20 cc. of 1N HCl was heated in a closed pyrex tube at 200° C., together with gold sheet, for 61 hours. Gold went into solution and precipitated, upon cooling, as small crystals; no gold was found to be present in solution. Considerably more gold was dissolved by HCl solutions of $FeCl_3$ than by HCl alone.

Similar results were obtained when ferric oxide and HCl were used in place of ferric chloride. Gold sheet was heated in a closed tube, together with 1 gram of ferric oxide and 20 cc. of 1N HCl, for 59 hours at 200° C. It was thought that by introducing ferric oxide in place of $FeCl_3$ some gold would remain in solution, as the ferric oxide in changing to magnetite would liberate oxygen with which the hydrogen from the HCl could combine, thus causing solution of gold. The reaction can be expressed by the following equations:

$$6Fe_2O_3 \rightarrow 4Fe_3O_4 + O_2$$
$$4Au + 12HCl + 3O_2 \rightarrow 4AuCl_3 + 6H_2O.$$

[36] Doelter, C.: *Op. cit.*, p. 328.
[37] Stokes, H. N.: *Op. cit.*, p. 550.

Some magnetite did form, but no gold was found in solution. A considerable amount of gold (0.0358 gram) had been dissolved but was all precipitated again on cooling (Table V).

TABLE V.

HIGH TEMPERATURE AND PRESSURE EXPERIMENTS WITH CHLORIDES AND Na_2CO_3.

No.	Material	Container	Gas	Hours	Temp. ° C.	Results
12.	1 gm. NaCl, 25 cc. H_2O.	Gold lined bomb	Air	56	300	Solution colorless. Gave no test for gold. When evap'd to dryness NaCl had a purplish tint due probably to colloidal gold
51.	3 gms. NaCl, 25 cc. H_2O.	Gold lined bomb	Air	$44\frac{1}{2}$	300	Results same as in above exp. Gold sheet etched in a few spots
22.	1.25 gms. NaCl, 25 cc. H_2O, 0.7293 gm. Au..	Pyrex tube	N	59	200	Solution gave no test for gold. Silica in solution. Weight of gold—0.7290
24.	1 gm. NH_4Cl, 25 cc. H_2O	Gold lined bomb	N	35	200	Solution colorless. Gave no test for gold. Gold sheet not etched
14.	1 gm. $FeCl_3.6H_2O$, 20 cc. 1N HCl, gold sheet.....	Pyrex tube	CO_2	61	200	Gold went into solution and was all pptd. again on cooling
21.	0.7651 gm. Au, 1 gm. Fe_2O_3, 20 cc. 1N HCl	Pyrex tube	N	59	200	0.0458 gm. gold went into solution and pptd. out on cooling. Some magnetite formed. Solution gave no test for gold
34.	0.7949 gm. Au, 2 gms. Na_2CO_3, 20 cc. H_2O..	Pyrex tube	N	$46\frac{1}{2}$	200	Solution colorless. Gave no test for gold. Silica in solution

Experiments with Sodium Sulphide.

Ever since Egleston [38] and Becker [39] made a number of experiments on the solubility of gold in alkaline sulphides, statements have appeared in the literature that gold is soluble in alkaline sulphides. Lenher [40] states that alkaline sulphides play an important part in the transportation of gold in nature.

[38] Egleston, T.: *Op. cit.*, p. 640.

[39] Becker, G. F.: *Op. cit.*, p. 209.

[40] Lenher, V.: *Op. cit.*, ECON. GEOL., vol. 7, p. 746.

Some of these experiments were repeated by the writer, and only in those that were made at high temperatures and pressures, with high concentrations of Na_2S, was any gold found to be present in solution, and then only as traces. Two experiments were made at room temperature, the details of which are given in Table VI. In one case, gold sheet was allowed to stand for 14

TABLE VI.

EXPERIMENTS WITH SODIUM SULPHIDE AT ROOM TEMPERATURE (CONTAINER—ERLENMEYER FLASK).

No.	Material	Gas	Time	Results
31a.	0.7578 gm. gold, 30 cc. 1N Na_2S.*	N	14 days	No loss in weight of gold
31b.	0.7578 gm. gold, 4 gms. $Na_2S.9H_2O$, 35 cc. H_2O	N	36 days	No loss in weight of gold

* Na_2S prepared by passing H_2S into NaOH for 1¾ hours and then adding an equal amount of NaOH.

days in a 1N Na_2S solution. The Na_2S was prepared by passing H_2S into NaOH, free from carbonate, for at least 1¾ hours and then adding an equal quantity of NaOH. The air in the flask was displaced by nitrogen. No gold was found in solution, and the weight of the gold sheet remained unchanged. In the second experiment gold sheet was allowed to stand for 36 days in a solution prepared by dissolving 4 grams of $Na_2S.9H_2O$ in 35 cc. of water. In this case also, no loss in the weight of the gold occurred.

A number of experiments were made to determine the solubility of gold in Na_2S under high temperature and pressure conditions. The results are given in Table VII. Some of the Na_2S used in the experiments was prepared by passing H_2S into NaOH, free from carbonate, for at least 1¾ hours and then adding an equal quantity of NaOH. A nitrogen atmosphere was used in most of the experiments. The water used for the solutions was first boiled for 10 minutes to expel the air dissolved in it. The experiments were made in a gold-lined bomb, because pyrex tubes are readily attacked by Na_2S. The temperatures of the experiments ranged from 175° to 300° C.

It will be seen from the results given in Table VII that no gold was found in solution when 0.5N and 1N solutions of Na_2S were used. In one of the experiments made with 1N Na_2S (prepared from carbonate-free NaOH) the gold sheet used for sealing the bomb was etched in a few spots. Some pure quartz sand between 100 and 200-mesh was introduced into the bomb, together with

TABLE VII.

HIGH TEMPERATURE AND PRESSURE EXPERIMENTS IN A *Gold-lined* BOMB WITH SODIUM SULPHIDE.

No.	Material	Gas	Hours	Temp. ° C.	Results
15.	25 cc. 1N Na_2S*.....	H_2S	$51\frac{1}{2}$	300	Solution colorless. Gave no test for gold
19.	25 cc. .5N carbonate free Na_2S,* fine quartz sand.....	N	22	300	Solution colorless. Gave no test for gold. Silica in solution. Gold sheet not etched
20.	25 cc. .5N carbonate free Na_2S*	N	25	300	Solution colorless. Gave no test for gold
23.	25 cc. 1N carbonate free Na_2S*.	N	$58\frac{1}{2}$	200	Solution colorless. Gave no test for gold. Gold sheet etched in a few spots
26.	5 gms. $Na_2S.9H_2O$, 25 cc. H_2O.	N	48	175	Solution had a greenish tint. Gave no test for gold. Gold sheet not etched
78.	6 gms. $Na_2S.9H_2O$, 25 cc. H_2O.	N	70	300	Solution colorless. Trace of gold in solution. Gold sheet etched slightly
73.	6 gms. $Na_2S.9H_2O$, 25 cc. H_2O.	CO_2	91	300	Solution had a greenish tint. Trace of gold in solution. Gold sheet etched slightly
48.	6 gms. $Na_2S.9H_2O$, 25 cc. H_2O.	Air	$43\frac{1}{2}$	300	Solution light greenish brown. Trace of gold in solution. Gold sheet slightly etched

* Na_2S prepared by passing H_2S into NaOH for $1\frac{3}{4}$ hours and then adding an equal quantity of NaOH.

Na_2S, in one of the experiments. The gold sheet was not etched and no gold was found in solution; much silica, however, had gone into solution.

Several experiments were made at 300° C. with solutions of 6 grams of $Na_2S.9H_2O$ in 25 cc. of water. In all these experiments only a trace of gold was found in solution, whether air,

carbon dioxide, or nitrogen was used as an atmosphere in the bomb. The gold sheet used for sealing the bomb was found to be slightly etched.

These experiments show that the amount of gold dissolved by Na_2S, either at room-temperature or at high temperatures and pressures, is very small.

Experiments with Sodium Hydrosulphide and Sodium Polysulphide.

Experiments made in a gold-lined bomb at high temperatures show that considerable quantities of gold are dissolved by solutions of sodium hydrosulphide (NaHS). The results are given in Table VIII. The NaHS was prepared by saturating a solution of Na_2S or NaOH with H_2S. The water used for preparing the solutions was first boiled to expel the air, in order to prevent oxidation of the NaHS to polysulphides. It was found that the amount of gold dissolved by NaHS increased both with the temperature and the concentration of the solution. A solution of NaHS (prepared by passing H_2S for ½ hour through an approximately 20 per cent. solution of $Na_2S.9H_2O$), heated for 90¼ hours at 200° C., dissolved 0.0323 gram of gold. NaHS of the same concentration and prepared in the same way, heated for 90 hours at 300° C., dissolved 0.0634 gram of gold. Only 0.0175 gram of gold was dissolved by a solution of NaHS (prepared by passing H_2S for ½ hour through a 7½ per cent. solution of $Na_2S.9H_2O$) heated for 90 hours at 300° C. Similar results were obtained when NaOH was used in the preparation of NaHS instead of Na_2S. In one of the experiments some commercial hardened silica gel was introduced into the bomb together with the NaHS. Nearly as much gold was dissolved in the presence of silica as in the experiment without silica. Only a relatively small amount of silica was dissolved by the NaHS. In the experiments with NaHS none of the gold precipitated from solution on cooling.

Two experiments were made to determine the solubility of gold in NaHS at room-temperature. The NaHS was prepared

TABLE VIII.

HIGH TEMPERATURE AND PRESSURE EXPERIMENTS IN A *Gold-lined* BOMB WITH SODIUM HYDROSULPHIDE AND SODIUM POLYSULPHIDE.

No.	Material	Gas	Hours	Temp. ° C.	Pts. per mil. of Au dissolved	Results
85.	6 gms. $Na_2S.9H_2O$, 25 cc. H_2O, H_2S passed into solution for ½ hr..	H_2S	90¼	200	1076	Solution yellow. 0.0323 gm. Au in sol'n. Gold sheet considerably etched
70.	5.8 gms. $Na_2S.9H_2O$, 25 cc. H_2O, H_2S passed into solution for ½ hr..	H_2S	90	300	2113	Solution yellow. 0.0634 gm. Au in sol'n. Gold sheet considerably etched
77.	2 gms. $Na_2S.9H_2O$, 25 cc. H_2O, H_2S passed into solution for ½ hr..	H_2S	90	300	648	Solution light green. 0.0175 gm. Au in sol'n. Gold sheet considerably etched
88.	3 gms. NaOH, 25 cc. H_2O, H_2S passed into solution for 1¾ hrs...	H_2S	63¾	300	1656	Solution greenish. 0.0447 gm. Au in sol'n. Gold sheet considerably etched
91.	3 gms. NaOH, 25 cc. H_2O, 2 gms. commercial silica. H_2S passed into solution for 1¾ hrs.....	H_2S	59½	300	1204	Solution light green. 0.0325 gm. Au in sol'n. Gold sheet considerably etched. Small amount of silica in solution
82.	6 gms. $Na_2S.9H_2O$, 0.2 gm. S, 25 cc. H_2O....	N	69	300		Solution colorless. Trace of gold in solution
86.	6 gms. $Na_2S.9H_2O$, 1 gm. NaOH, 0.4 gm. S, 25 cc. H_2O.....	N	48	300		Solution light brown. Trace of gold in solution. Gold sheet slightly etched

by passing H_2S for ½ hour into 7 per cent. and 20 per cent. solutions of $Na_2S.9H_2O$ respectively. The solutions were placed in flasks and the air was displaced by H_2S. The flasks were stoppered and kept in the dark for 29 days. After a few days

the solutions turned yellow, indicating the formation of higher sulphides, possibly due to oxidation. There was a small loss in the weight of the gold in both experiments and the solutions gave a weak test for gold (Table IX).

TABLE IX.

EXPERIMENTS WITH SODIUM HYDROSULPHIDE AT ROOM TEMPERATURE (CONTAINER—ERLENMEYER FLASK).

No.	Material	Gas	Time	Results
89.	2.3 gms. $Na_2S.9H_2O$, 30 cc. H_2O, 0.5372 gm. Au, H_2S passed into solution for ½ hour	H_2S	29 days	Solution yellow. Loss of 0.0005 gm. in weight of gold
90.	7 gms. $Na_2S.9H_2O$, 30 cc. H_2O, 0.7490 gm. Au, H_2S passed into solution for ½ hour	H_2S	29 days	Solution dark yellow. Loss of 0.0008 gm. in weight of gold. Solution gave a test for gold

The results of the experiments with Na_2S and NaHS indicate that gold is carried in solution by NaHS and not by Na_2S. Also, NaHS rather than Na_2S would be found in nature, as Na_2S hydrolyzes almost completely into NaHS and NaOH, and the latter in the presence of silica would form Na_2SiO_3. The reaction due to hydrolysis and attack of silica may be expressed by the following equations:

$$Na_2S + H_2O \rightleftarrows NaOH + NaHS$$
$$2NaOH + SiO_2 \rightarrow Na_2SiO_3 + H_2O.$$

Alkali sulphides have often been cited as solvents of pyrite, pyrrhotite and other metallic sulphides. Recently, however, the solvent action of the alkali sulphides has been questioned. Gruner [41] states that hot alkali sulphide solutions do not play an important rôle as carriers of metals, except possibly in the case of antimony, arsenic, and mercury.

Sodium polysulphide, prepared by dissolving sulphur in a solu-

[41] Gruner, J. W.: The Solubilities of Metallic Sulphides in Alkali Sulphide Solutions. ECON. GEOL., vol. 28, p. 777, 1933.

tion of Na_2S, was found to have little solvent action on gold at high temperatures and pressures (Table VIII). Only traces of gold were found in solution.[42] Although the solutions were yellow when they were prepared, they were colorless when removed from the bomb. As sodium polysulphide solutions are yellow, it appears that some chemical change occurred in the solutions during the experiments.

SUMMARY AND CONCLUSIONS.

1. 20 per cent. hydrochloric acid vapor in a dynamic system has no action on gold between 250° and 600° C.

2. When chlorine and steam are passed over gold, $AuCl_3$ is formed. The volatilization of $AuCl_3$ in the presence of chlorine and steam begins below 125° C., increases rapidly to a maximum at 200° C., and then decreases rapidly to almost nothing at 400° C. The decrease in the amount of volatilization above 200° C. is due to the fact that around this temperature the dissociation pressure of the $AuCl_3$ increases much more rapidly than the vapor pressure. It is possible that the presence of water vapor may have an effect on the temperature at which maximum volatilization takes place. Pressure would tend to prevent dissociation and would, therefore, affect the temperature of maximum volatilization.

3. Gold dissolves in weak hydrochloric acid at high temperatures and pressures. The amount dissolved increases with the concentration of the acid and the temperature and pressure. Pressure is an important factor in causing solution. Larger quantities of gold are dissolved in the presence of air than in the presence of carbon dioxide or nitrogen.

4. The writer did not find that aqueous solutions of alkali chlorides have an appreciable solvent action on gold in the presence of air or nitrogen and under high temperature and pressure conditions, although Lenher reports that they have.

5. Sodium carbonate was not found to have solvent action on gold at high temperatures and pressures. This is not in agreement with Doelter's work.

[42] The water used for preparing the solutions was first boiled to expel the air. The air in the bomb was displaced by nitrogen.

6. Stokes found that gold dissolves in hydrochloric acid solutions of ferric chloride at high temperatures and pressures and in the absence of oxygen. This was confirmed by the writer.

7. The writer found that Na_2S solutions dissolved only traces of gold at high temperatures and pressures, and none at room temperature. These results do not agree with those of Becker, Egleston, and Lenher.

8. On the other hand, considerable quantities of gold are dissolved by solutions of NaHS at high temperatures and pressures. Some gold is also dissolved by NaHS at room temperature.

In this investigation an attempt was made to imitate as closely as possible the conditions existing in nature. The experimental evidence shows that gold may be transported either in acid or slightly alkaline aqueous solutions and also in the vapor phase as $AuCl_3$. In acid solutions, gold is probably carried as a chloride. Precipitation from chloride solutions would result when the solutions come in contact with one of the many reducing agents which occur in nature. In hot alkali hydrosulphide solutions, gold is probably carried as a double sulphide of the alkali metal and gold. Oxidation or acidification of the solution would cause precipitation.

In a closed system, the partial pressures of $AuCl_3$ and its dissociation products would tend to prevent both volatilization and dissociation of the chloride after an equilibrium has been reached. Therefore, under high temperature and pressure conditions $AuCl_3$ is probably not carried in the vapor state. However, under somewhat reduced pressure conditions when the solutions and gases are in communication with the earth's surface, gold may be transported in the vapor phase as $AuCl_3$. It is difficult to place limits on the temperature at which volatilization would take place in Nature, as the pressure factor is uncertain.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
Sept. 6, 1934.

QUANTITATIVE STUDY OF ORE ZONING, AUSTINVILLE MINE, WYTHE COUNTY, VIRGINIA.[1]

W. HORATIO BROWN.

THE Austinville Mine of the Bertha Mineral Company, New Jersey Zinc Company subsidiary, is situated on the New River three miles northeast of the point where it cuts through the Blue Ridge Mountains into the Valley of Virginia.

As an adequate description of the geology of these ore deposits is lacking, the following brief summary will present a background for the account of the detailed zonal studies. It is hoped that at some time in the future a detailed description of this ore occurrence may be published by the writer and his associates.

The ore bodies of the Austinville mine are fracture-filling and replacement deposits in the Shady limestone of Lower Cambrian age. The deposit is situated on the south limb of the Austinville anticline and is localized in rock intensely fractured by the action of strike and cross faults. In general, the ore bodies parallel the strike faults and are greatly enlarged at cross-fault intersections where the ore bodies are distinctly cross-cutting. This relationship is clearly shown on Fig. 1, a map of a mine level. They are further localized stratigraphically in the massive dolomites at contacts[2] with less competent beds in the series, causing the largest single ore body to have an almost plane footwall inclined along the incompetent bed, and a dome-shaped top. Intense recrystallization of the country rock is associated with the ore. The combination of structural control by strike faults and stratigraphic control by incompetent beds has caused the ore bodies to

[1] Published by permission of Mr. Henry Hardenbergh, General Manager of Mines and Manufacturing, The New Jersey Zinc Co.

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[2] The writer hopes to discuss this relationship at a later date, and believes that it represents a principle of wide application in the preparation of ground for ore deposition, especially in districts where pre-mineral thrusting is of importance.

have a pipe-like form, with enlargements near cross faults. Both strike faults and cross faults were apparently due to compression, although the cross faults are of the so-called " normal " type.

The deposits are mineralogically simple. The early production of the mine was from oxidized residual deposits in red clay on the pinnacled surface of the dolomite, but these need not be considered here. Sphalerite is the principal sulphide mineral and is usually light brown in color, although a subordinate quantity of light rosin sphalerite is found. Pyrite is common, as is also galena. Marcasite is apparently present, although it has not been positively identified. The principal gangue mineral is dolomite, which is clearly of introduced origin, although at places it is difficult to distinguish epigenetic dolomite from recrystallized dolomite wall rock. Silicification of the wall rock fragments in the ore breccias is locally prominent. Crystalline quartz is relatively rare. Fluorite and calcite occur in small quantities, and barite is rare.

THE PROBLEM.

The study of the zonal deposition of ores has received considerable attention since 1900, and since 1922 has been progressing [3] rapidly. However, in spite of this, the writer knows of but one case where a quantitative study of metal ratios in a mine or district has been published. Broderick [4] showed that there is a progressive change in the copper-arsenic ratio in the copper ores of Michigan in depth, as well as in detail where the ores are associated with fractures. He was able from these changes to determine the probable direction of travel of the solutions that deposited the ores. A knowledge of the direction of travel of the ore-depositing solutions is of great value in planning

[3] Spurr, J. E.: The Ore Magmas. New York, 1923. Emmons, W. H.: Primary Downward Changes in Ore Deposits. Tr. Amer. Inst. Min. Eng., vol. 70, pp. 964–997, 1924. Broderick, T. M.: Zoning in Michigan Deposits. Econ. Geol., vol. 24, pp. 149–162 and 311–326, 1929. Emmons, W. H.: Origin of Sulphide Ores of the Mississippi Valley. Econ. Geol., vol. 24, pp. 221–271, 1929. Broderick, T. M.: Fissure Vein and Lode Relations in Copper Deposits. Econ. Geol., vol. 26, pp. 840–856, 1931.

[4] *Op. cit.*, Econ. Geol., vol. 24, 1929.

the development work in any deposit. The following work was undertaken with the hope that a study of the distribution of the metal ratios in the Austinville mine would throw some light on this problem.

THE DATA.

The Austinville Mine is developed by drifts in the footwall of ore bodies, with cross-cuts to the hanging wall at one hundred foot intervals. All of the workings in ore have been sampled by staggered stoper drill holes at five-foot intervals in the cross cuts and ten-foot intervals in the drifts. A total of 2136 samples were used in this study. Analyses of these samples for zinc, lead and iron were available.

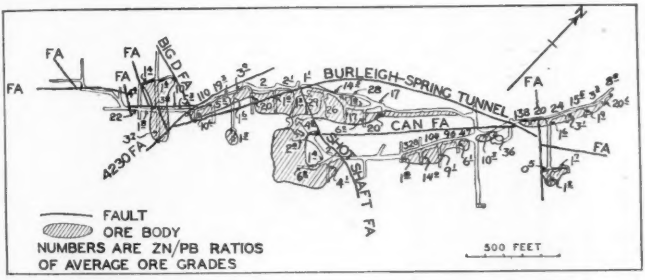

FIG. 1. Plan of a centrally located level, showing Zn-Pb ratios.

METHOD OF ATTACK.

From the analyses, ratios were computed and plotted as graphs. The following ratios were determined: Zn/Pb, Fe/Pb, and Fe/Zn. These ratios were plotted to scale horizontally, as shown by the location of the samples on the assay maps, and the vertical scale was arbitrarily determined to best represent the data. Graphs were made for all mine workings that penetrate ore, and a total of 94 detailed graphs, showing each sample, were constructed (Figs. 2–3). Samples were also averaged for 100-foot intervals in the mine, and maps and isometric projections of parts of the mine were made showing the ratios of the average grade of ore

for 100-foot intervals. Extra graphs were made for the mine as a whole which showed the change in ratio longitudinally along the ore zone and vertically by levels, as well as several additional graphs showing changes in ratios with depth on single cross sections.

RESULTS.

The detailed graphs of the individual openings and the maps and drawings of the mine showing the ratios in larger blocks have been analyzed separately, and an attempt has been made to correlate these with the geologic maps of the workings. In general,

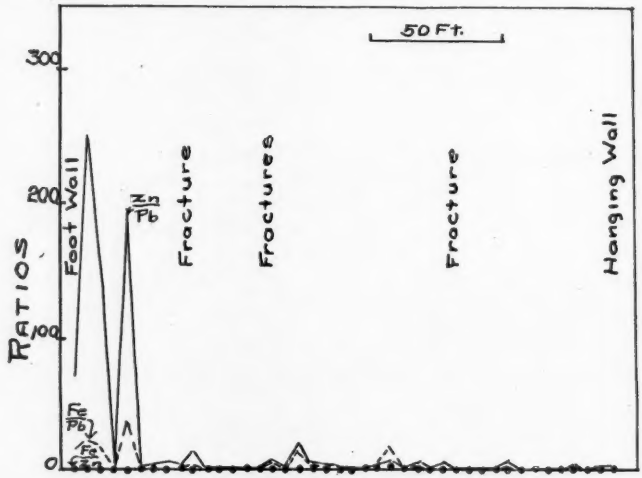

FIG. 2. Detail ratio graph of a cross-cut.

as might be expected, the detailed graphs are minutely irregular and in places difficult to rationalize, and the maps showing ratios of larger blocks bring out the larger, more important features.

Detailed Graphs.—The detailed graphs showing the ratio of each sample in a given opening have been studied with a view of correlating the highs [5] on the graphs with structural features.

[5] By "high" is meant a point higher than adjoining points on that part of the graph. In other words, the terms high and low are used relatively and with reference only to that part of the graph under consideration.

Fig. 2 is a typical graph of a cross-cut. This shows the variation in ratio for individual samples and the decided tendency for high ratios to occur at the footwall.

Fig. 3 is a detailed longitudinal graph of the ratios along the footwall of one of the ore bodies. This graph is based on samples along the southeasternmost drift northeast of the Shot Shaft Fault (Fig. 1). Since footwall ratios are high, this curve is made up of high ratios. In spite of the irregularities, two features stand out prominently. There is a decrease in ratio northeastward from the Shot Shaft Fault, and a slight increase followed by a decrease after passing the Spring Tunnel Fault. This graph

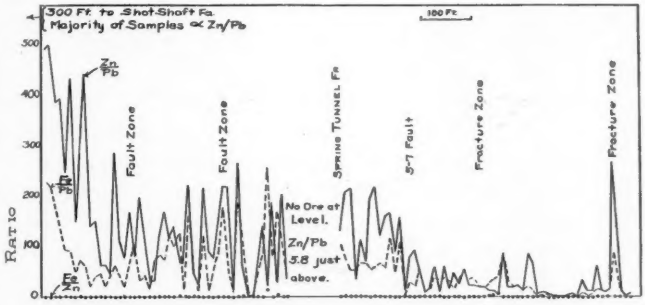

FIG. 3. Detail ratio graph, footwall of an ore body.

is made from samples taken on an intermediate level. The ore body northeast of the Shot Shaft Fault plunges northeasterly; therefore there is ore above the level between the southwesternmost samples shown and the fault. Information from drill holes shows that the footwall part of the ore body near the fault has no lead and shows an infinity ratio in the majority of holes.

A statistical analysis of the 94 detailed graphs shows that the footwall of the ore has high ratios in 68 per cent. of the cases. The Burleigh-Spring Tunnel Fault has high-ratio ore associated with it in 78 per cent. of the penetrations, and other faults have between 64 and 67 per cent. high-ratio ore associated with them.

Generalized Results.—Fig. 1 is a somewhat generalized map of

a level of the mine showing ore bodies, ratios by one hundred foot averages, and the more important faults. Since this level is the most centrally located in the ore bodies, it shows the ratio relationships more clearly than any other. Near the southwest end of the level there is an intersection of the Big D with two other faults. Northeast of this fault the ratios are high, gradually decreasing toward the Shot Shaft Fault. Near this fault the structure is complex and the ratios are erratic. In the southern drift it will be seen that high ratios are encountered northeast of the Shot Shaft Fault and decrease northeastward towards the Burleigh-Spring Tunnel Fault. This is the same drift shown on the detailed longitudinal graph, Fig. 3, and high ratios are found in the ore above the level in the immediate vicinity of the fault.

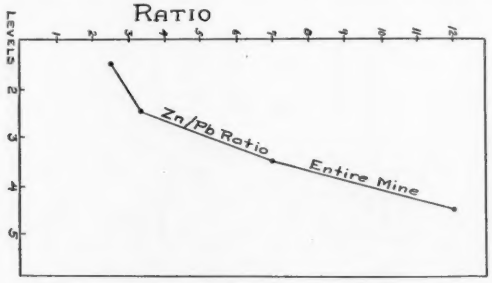

FIG. 4. Graph of ratios by levels.

Fig. 4 is a graph illustrating the change in Zn/Pb ratio with depth. The ratios on this graph were determined by the following method: The average grade of ore in each stope block was determined by the customary procedure; the percentage of zinc and of lead was multiplied by the tonnage in the block to give the zinc and lead units present; these units for the stopes were added to give the total units between levels, and the total zinc units were divided by the total lead units for the ratios between the levels. This graph shows a striking increase in ratio with depth.

Summary.—The foregoing analysis of the distribution of ratios brings out several points. There is a strong concentra-

tion of high ratios at faults, especially the three—Burleigh-Spring Tunnel Shot Shaft and Big D—on the footwall of ore, and on most of the fifth level where infinity ratios are abundant.

Further, it can be seen clearly that the ratios decrease outward and usually northeastward from the faults, and upward from the footwall. Also, there is a striking increase in ratio with depth.

INTERPRETATION.

The change in metal ratios described above is in agreement with that demanded by the principle of zonal deposition. On this basis it may be tentatively concluded that the solutions that deposited the ore rose principally along the Shot Shaft, Burleigh-Spring Tunnel and Big D faults and spread out first along the footwall and then upward into the less brecciated dolomite. On account of the plunge of ore shoots, the trend of the solutions locally must have had a downward component.

Previous quantitative studies of the stratigraphic distribution of ore and of the distribution of types of brecciation, i.e., ground preparation, indicated the footwall to be the best prepared section for ore bodies. This work on ratios may be regarded as a check on those studies.

Several features require further discussion. The effect of the plunge of the ore shoots northeastward through the plane of the levels on which the mine samples are taken, undoubtedly accounts for a small part of the horizontal change in ratios, but, except for a few unusual cases, the effect is not believed to be important. In the case shown on the longitudinal graph, Fig. 3, the effect is certainly not important, since still higher-ratio ore is known up the plunge toward the fault.

It can be seen (Fig. 1) that in several areas the ratios are erratic. These areas of erratic ratios are almost invariably areas of complex structure, and it is probable that in such areas ore-bearing solutions would travel through minor as well as major faults into the brecciated dolomite. Outside of such areas the distribution of ratios is much more uniform.

Another noteworthy feature is the lack of parallelism between

the graphs of the Fe/Zn ratio and the graphs of the other two ratios. This is much more marked on the upper than on the lower levels. It is probably due to the presence of unrecognized marcasite in the ore; locally this is almost certainly the cause. Microscopic work now in progress will probably throw some light on this problem.

ORIGIN OF THE ORE.

On a previous page the writer stated that it might be tentatively concluded on a basis of the zoning or ratio changes brought out in this study that the ore was deposited by solutions rising along the controlling faults and spreading outward along the footwall and upwards into the brecciated zones. It is realized that ratios may be interpreted in a different manner, *i.e.*, it might be suggested that the solutions emanated from the unbroken country rock and gradually travelled toward the faults and downward along them.

As a test for these two interpretations, the writer desires to propose a criterion. In a previous paper [6] it was shown that there is a definite relationship between zoning and the order of paragenesis of the zoned minerals. Fowler and Lyden suggested [7] that the orderly and unrepeated sequence of the cycle of rock alteration and mineralization was strong evidence for magmatic origin in the Tri-State District. The writer suggests that if the ores were deposited by rising solutions at Austinville, the order of deposition of the minerals in the ores should be pyrite, sphalerite and galena. Galena might, on account of concentration, be deposited earlier in the low-ratio zones. Conversely, if the solutions travelled inward and downward, the order of paragenesis would have to be galena, sphalerite and pyrite.

So far, only five or ten selected specimens from low and high-ratio zones have been polished and studied. These, as well as macroscopic examination throughout the mine, show that galena

[6] Brown, W. Horatio: Mineral Zones of The White Cross District, Colo. Colo. School of Mines Mag., vol. 15, pp. 5–15, 1926.

[7] Fowler, G. M., and Lyden, J. P.: The Ore Deposits of the Tri-State District (Discussion). ECON. GEOL., vol. 28, p. 76, 1933.

is always later than sphalerite and pyrite appears to precede sphalerite.

On this basis, the writer concludes that the ores were deposited by rising solutions. Whether the solutions were of magmatic origin it is impossible to demonstrate locally, but it is difficult for the writer to believe that the intense recrystallization of the dolomite associated with the ore could have been caused by cold waters. Also, this deposit fits into the system of zoning, mentioned by W. H. Emmons,[8] about the late Paleozoic granites of the southern Appalachians.

The interpretation of an origin by rising magmatic waters appears to be indicated for this deposit, even though no intrusives are known near-by. The deposit should, therefore, be tentatively classified as a low-temperature magmatic deposit.

ACKNOWLEDGMENTS.

The summary of the geology of Austinville at the beginning of this article is a result of the joint work of Mr. W. H. Callahan and the writer, assisted later by Mr. S. S. Goodwin. In the zonal study the writer was assisted in computing and plotting ratios by Mr. Goodwin and Mr. James Bunten, and is indebted to all three for criticism.

GILMAN, COLO.,
Nov. 3, 1934.

[8] *Op. cit.*, ECON. GEOL., vol. 24, p. 271.

THE COPPER ORES OF ORANGE COUNTY, VERMONT.

N. W. BUERGER.

INTRODUCTION.

During the course of a field trip to the Vermont copper deposits in October, 1927, some rather coarsely crystalline chalcopyrite was collected, along with other ores, at the Orange county mines. Microscopic examination proved this to contain well developed cubanite-chalcopyrite intergrowths. Since this has been a subject of considerable interest, an examination of the ores was recently carried on. The results of the crystallographic investigation, including the unique determinations of the cubanite plate orientation and new chalcopyrite twin lamellae, appear separately.[1] The present paper presents the results of the metallographic and petrographic study of polished and thin sections of the ores.

LOCATION OF THE DISTRICT.

The deposits lie in the eartern foothills of the Green Mountains in Orange County, Vermont, 7 to 10 miles west of the Connecticut River. The copper belt lies in the townships of Corinth, Vershire, and Strafford, and trends north-south for about 10 miles. Fig. 1 shows the locations of the three principal mines: the Pike Hill, the Ely or Copperfield, and the Elizabeth-Foster-Cleveland.

Pike Hill Mine, the most northerly of the group, is in the township of Corinth about 1½ miles north of the village of West Corinth. The Ely mine, about 11 miles to the south, is in Vershire township, ½ miles north of the village of Ely. The

[1] Buerger, N. W., and Buerger, M. J.: The Crystallographic Relations between Cubanite Segregation Planes, Chalcopyrite Matrix, and Secondary Chalcopyrite Twins. Amer. Miner., vol. 19, pp. 289–303, 1934.

Elizabeth-Foster-Cleveland property, 6 miles farther to the south, is in the township of Strafford, about ½ mile southwest of the village of Copperaskill.

The specimens examined come largely from the Pike Hill Mine and are representative of the district as a whole.

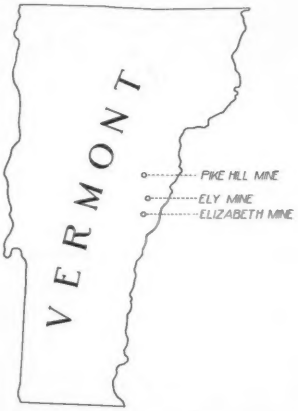

FIG. 1. Sketch map showing location of mines.

GENERAL DESCRIPTION OF THE DISTRICT.[2]

The ore bodies occur on the eastern flank of a broad anticlinal fold, pitching north, in which the rocks for the most part are metamorphic sediments of probably Paleozoic age. The oldest rocks exposed in the southern axial portion of this anticline are mica schists, containing calcite, to which the geologists of the Vermont and New Hampshire Surveys have given the name calciferous mica schist; these have been tentatively considered to be Silurian. This formation passes upward into rocks containing much more calcite, so that finally, on the northern and western sides of the fold, the lower rocks are partially surrounded by an incomplete ring of impure, partly recrystallized limestones,

[2] Smyth, H. L., and Smith, P. S.: The Copper Deposits of Orange County, Vermont. Eng. and Min. Jour.-Press, vol. 77, pp. 677–678, 1904.

interstratified with bands of calcareous mica schist. On the eastern side of the arch the more calcareous rocks appear to be lacking.

Overlying the calcareous member, on the western side of this fold, are formations of slate, including some areas of roofing slate. The stratigraphic succession across this anticline is therefore as follows: The lowest member consists mainly of mica schists, containing some calcite; these are overlain by impure limestones, interstratified with mica schists; these in turn are succeeded by mica slates or phyllites.

Besides these metamorphic sediments, igneous rocks, both acid and basic, occur in the district. The acid rocks consist of numerous dikes of fine- to medium-grained biotite granite, which is lithologically identical with the well-known Barre granite, a portion of which extends into the north-central part of Orange county. In addition, a few dikes of coarser acid pegmatite are found, which cut the granite in some localities. From their relations and lithological character, the pegmatite dikes seem to have proceeded from the same magma as the granite. They commonly contain a little pyrrhotite, chalcopyrite, and black tourmaline. It is believed that the intrusion of the granite has played an important part in the genesis of the ore deposits.

THE ORES.

The Orange county ore-bodies occur in the lower formations of the mica schists, in what is called by C. H. Richardson [3] the Bradford schist. They have been formed mainly by replacement, at the Elizabeth-Foster-Cleveland mine along a fault fracture, at the Ely and Pike Hill mines along openings formed by folding which occurred subsequent to the main folding.

Pyrrhotite is the principal mineral in the ore, occurring intimately and in varying proportions with chalcopyrite. The copper content ranges from 0.3 to 20 per cent; the average grade mined in early operations was probably 3 per cent. Modern methods of concentration, however, made the handling of ore averaging less than 2 per cent copper economically possible [4] (March, 1930).

[3] Richardson, C. H.: Fifth Ann. Rept. State. Geol., Vermont, 1906.

[4] Anderson, C. S.: Mining and Milling in the Vermont Copper District. Eng. and Min. Jour.-Press, vol. 131, pp. 208–210, 1931.

The Metallic Minerals.

The following minerals were identified in a microscopic study of polished sections of the ore from the Pike Hill and the Ely mines: Pyrite, pyrrhotite, chalcopyrite, cubanite, valleriite, sphalerite, galena, hematite.

Pyrite.—Pyrite occurs in only one specimen of those examined. This is from the Ely mine. It is in the form of a dense aggregate of angular fragments, evidently the result of the fracturing of a large mass. The spaces between the fragments are occupied by quartz, chalcopyrite, sphalerite, and a trace of galena. Where present, pyrite was the first mineral to be deposited.

Pyrrhotite.—Pyrrhotite, together with chalcopyrite, makes up the bulk of the metallic minerals. By far the greater amount of pyrrhotite in the ores is massive, showing no crystal outlines. Under crossed nicols, these masses were seen to be made up of fairly large crystals, characteristically anisotropic. Under ordinary reflected light, the separate crystals show a parallel parting; when etched for a short time with a solution of 12 cc. concentrated $K_2Cr_2O_7$, 100 cc. water, and 3 cc. concentrated H_2SO_4 (specific gravity 1.84), this direction proved to be that of the twinning.

The pyrrhotite occurs in two more or less distinct relations with the later sulphides—as alternating bands with chalcopyrite, and as intimate intergrowths with chalcopyrite and other sulphides.

The boundaries between the pyrrhotite and chalcopyrite are for the most part smooth and regular. However, there are some sharp embayments in the pyrrhotite into which the chalcopyrite projects. These are invariably associated with fractures running through the pyrrhotite. In some cases these fractures are filled for short distances with chalcopyrite. Peninsulas of pyrrhotite jut out from the main mass of pyrrhotite into the chalcopyrite, and may be isolated from the main mass by cross-cutting veinlets of chalcopyrite. These relations indicate that the pyrrhotite was deposited before the chalcopyrite.

Chalcopyrite occurs both as fine-grained interstitial filling in the fractured pyrite, and as coarse massive aggregates and bands.

Some of the separate crystals are as large as 10 mm. When examined with polarized light, the separate crystals are distinguishable, and show the *grid* and the *echelon* type of secondary twinning parallel to the prism {110} and the sphenoid {101} planes of the chalcopyrite respectively.

Laths of cubanite are observable in both natural reflected and polarized light in intergrowth with individual chalcopyrite grains. The relationships existing between the chalcopyrite, its twinning, and the cubanite segregate are discussed in detail in a separate paper.[5]

Valleriite also occurs in the chalcopyrite, and will be discussed below.

Sphalerite is present in the chalcopyrite as irregular blebs and as minute stringers connecting small lenticular masses of sphalerite. The age relations of the irregular blebs are lacking; the boundaries are smooth and sharp. The stringers and lenticular masses, however, are definitely later than the chalcopyrite and follow grain boundaries and fractures. Sphalerite is also commonly found at the boundaries between pyrrhotite and chalcopyrite. The stringers and veinlets in some cases persist into the pyrrhotite from the chalcopyrite, placing some sphalerite later than both minerals.

Cubanite occurs as plates within individual grains of chalcopyrite along the sphenoid {111} planes, and appears as bands in the chalcopyrite on a polished section. It shows a negative relief to the chalcopyrite, apparently being slightly softer. In natural reflected light, the cubanite is lighter than the chalcopyrite, and in reflected polarized light it is more anisotropic. Its relation to chalcopyrite has been mentioned under chalcopyrite and is described in detail in a separate paper.[6]

Valleriite.—Valleriite, formerly known as "unbekanntes Nickelerz,"[7] has recently been redescribed by Ramdohr and Ödman.[8]

[5] Buerger, N. W., and Buerger, M. J.: *Op. cit.*

[6] Buerger, N. W., and Buerger, M. J.: *Op. cit.*

[7] Schneiderhöhn, H., and Ramdohr, P.: Lehrbuch der Erzmikroskopie, Bd. II, pp. 127–130, Berlin, 1931.

[8] Ramdohr, P., and Odman, O.: Vallariit. Geol. Fören. Förhandl., Bd. 54, H. 1, pp. 89–98, 1932.

It is a copper-iron sulphide ($Cu_2Fe_4S_7$). The mineral has been identified by the writer in the ores from the three mines of this district, as well as in similar ores from other localities.[9] In reflected light, valleriite is very similar in appearance to pyrrhotite, but has more of a rose tint, and is very soft, its hardness being about that of graphite. In polarized light it is brilliantly anisotropic; this characteristic will immediately distinguish valleriite from pyrrhotite. Reflection pleochroism is strong: pale yellow toward rose, to dull gray, somewhat bluish. Etching is negative with HCl, HNO_3, aqua regia, KCN, KOH, $FeCl_3$, $HgCl_2$.

Valleriite occurs within the chalcopyrite in two ways—as segregations forming small crosses, and as minute veinlets and worm-like masses. The crosses are somewhat similar to sphalerite crosses, but are much sharper in outline, consisting of two simple lines crossed, rather than the skeleton crystals common in sphalerite crosses. One of the lines forming the cross is generally shorter than the other, giving a dagger-like appearance. The veinlets and worm-like masses of valleriite tend to be near the pyrrhotite border rather than far out in the chalcopyrite, while the cross-type appears throughout the chalcopyrite.

Because of its unvarying orientation when occurring in the form of small crosses in any individual grain of chalcopyrite, and because its composition ($Cu_2Fe_4S_7$) would permit the possibility of its being a product resulting from the unmixing of a complex iron-copper-sulphide solid solution, the writer considers it probable that valleriite may be the result of such an unmixing. Schwartz [10] has shown that cubanite is the product of the breaking down of a solid solution, and it is not unlikely that the valleriite may be of similar origin.

The crystallographic relations obtained between the valleriite and the chalcopyrite have not been investigated in enough detail

[9] It may be mentioned at this time that the writer has identified valleriite in the ores from the Frood mine, Sudbury, Ontario, and in specimens from Prince William Sound, Alaska. These ores are in some respects similar to those of the Vermont copper deposits.

[10] Schwartz, G. M.: Intergrowths of Chalcopyrite and Cubanite: Experimental proof of the origin of the intergrowths and their bearing on the geologic thermometer. ECON. GEOL., vol. 22, pp. 44–61, 1927.

to offer any definite statement at this time as to what these relations are, but a detailed study of the problem is being carried on by the writer.

Sphalerite occurs mainly in the chalcopyrite, more rarely in the pyrrhotite. Its relations have been discussed in the description of chalcopyrite. Part of the sphalerite, at least, is definitely later than both pyrrhotite and chalcopyrite. The age relations of the irregular masses are obscure.

Galena.—Only one occurrence of galena, from the Ely mine, was noted in the specimens studied. It occurs in the form of a small irregular mass intergrown with the quartz, chalcopyrite, and sphalerite, which fills the fracturing of the pyrite. Age relations are lacking, except that the galena is later than the pyrite.

Hematite has been found only in the pseudodiorite type of rock which is described further on, and in one other section. The crystals are arranged in bands paralleling the general schistosity of the adjoining rock. This is clearly a residual mineral, since it is included by all of the other minerals present.

The Nonmetallic Minerals

A brief examination of the nonmetallic minerals has been made. The limited study of these minerals shows that the silicates in the ore and wall rock are about the same as those in the general country rock. It has not been possible in this study to separate the two types. Therefore a listing of the minerals identified in thin section will be given, together with a brief description and a few general remarks. The minerals identified are as follows: quartz; feldspars (orthoclase (?), microcline, oligoclase-andesine); carbonates (calcite, dolomite); micas (phlogopite, muscovite); chlorite, hornblende, garnet, vesuvianite or zoisite, titanite, apatite, zircon, tourmaline (dravite), rutile, kyanite.

The rock is, for the most part, a phlogopite-muscovite schist. Quartz occurring as bands is the most abundant and wide-spread of the nonmetallic minerals. There are two distinct types of the mineral. One is rather coarse-grained, and bands of this seldom include any other minerals except rare phlogopite plates, found

mostly along grain boundaries or in fractures. The second type is fine-grained, and is intimately associated with other minerals, notably the feldspars and micas.

The plagioclase feldspar is dominantly oligoclase-andesine; microcline is abundant, and untwinned feldspar (orthoclase?) occurs sparingly. Of the micas, phlogopite is first in abundance. It commonly forms bands with the blades oriented parallel to the direction of schistosity. Rutile and zircon are common inclusions. The phlogopite may also form the nucleus of the muscovite blades. Sericite is present in the more calcic portions of the rock. It is also an alteration product of the potash feldspar. Chlorite is only sparingly present.

Hornblende and tourmaline are mainly confined to the pseudodiorite type of rock. Garnet is quite abundant throughout, and is much fractured. Two types of carbonate are present. One is coarsely crystalline and may well be remnants of calcite or crystalline limestone from the original rock. The other is a fine-grained aggregate which is undoubtedly an introduced mineral.

Titanite occurs sparingly in characteristic wedge-shaped crystals. Apatite is found widely distributed in rather large rounded crystals.

A mineral which is either vesuvianite or zoisite, although not abundant, is found widespread. The crystals are prismatic, with the long axis parallel to the direction of schistosity. Large crystals of kyanite are found in the adjoining country rock.

The thin sections show the rocks to have been subjected to stress, with the development of undulatory extinction in the quartz and feldspars, mortar structure of the quartz, distortion of the micas, and fracturing throughout.

Apparently there has been some introduction of quartz, tourmaline, apatite, carbonate, chlorite, possibly titanite, with some garnet, and phlogopite.

Nodules of coarsely crystalline limestone are found in the ore zone, and are very similar to those of the Ducktown, Tennessee, copper deposits. The nodules have a sharp boundary, and range in size up to several inches.

Of special note is the occurrence of a rock similar to the pseudodiorite of the Ducktown deposits. This rock consists mainly of hornblende, quartz, feldspars, phlogopite, chlorite, garnet, and zircon, with needles of hematite running through all the minerals in parallel bands. This hematite has the same pattern or arrangement as that of the hematite in the adjoining schist. It is regarded as a residual mineral, which has not been affected by the reorganization of the schist to form pseudodiorite.[11] This gives strong support to the theory of the formation of pseudodiorite at Ducktown, as given by Emmons and Laney.[12]

Some points of similarity with the Ducktown, Tennessee, deposits should be noted, chief of which are the mineralogy, and the local presence of residual marble in the ore zone, which has the same sharp boundary and coarse crystallization as the marble in the ores at Ducktown. A further point of resemblance is the presence of a rock similar to the pseudodiorite found at Ducktown.

SUMMARY.

The suite of ores from the Orange County, Vermont, copper district represents a deposit of the high-temperature type. The silicate minerals of the ore and wall rock are closely similar to those in the country rock. The most abundant of these are quartz, microcline, oligoclase-andesine, calcite, phlogopite, muscovite, and garnet. Of the ore minerals, pyrite was the first to be deposited, followed by pyrrhotite, then chalcopyrite. Sphalerite is, at least in part, later than both pyrrhotite and chalcopyrite. The mutual age-relations of the cubanite and valleriite could not be determined because of the peculiar location of the cubanite and valleriite as segregates in the chalcopyrite matrix. The age of the galena relative to the other minerals is obscure in the specimens at hand. Hematite is relict. The deposit is similar in many respects to the Ducktown, Tennessee, copper deposits.

[11] Emmons, W. H., and Laney, F. B.: Geology and Ore Deposits of the Ducktown Mining District, Tennessee. U. S. Geol. Survey, Prof. Paper 139, pp. 19–21, 1926.

[12] *Idem.*

ACKNOWLEDGMENTS.

The author is indebted to Dr. W. H. Newhouse for his helpful criticisms and suggestions. Dr. Waldmar Lindgren was kind enough to read the manuscript and offer further suggestions.

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CAMBRIDGE, MASS.,
Aug. 13, 1934.

DISCUSSION AND COMMUNICATIONS

ORIGIN OF CYANITE.

Sir: The November, 1933, number of this journal contained a discussion by Mr. J. A. Dunn entitled, "Andalusite in California and Kyanite in North Carolina," in which he referred to the aluminous silicates—andalusite, sillimanite, and cyanite—and criticized my paper on "Cyanite Deposits of North Carolina."[1] His objections to it are: (1) The limited area of study and the use of laboratory rather than field evidence, (2) the casual use of the term "replacement," and (3) the suggestion that cyanite was formed by hot solutions.

As compared with Singhbhum, India, where cyanite occurs over a belt nearly 100 miles long, the deposits of North Carolina occur in an area nearly 300 miles long, of which the most important part is a belt of about 175 miles along the Appalachian Mountains in which cyanite outcrops are almost continuous. This belt extends into Virginia and Georgia. The descriptions and conclusions regarding the cyanite deposits of these states are similar to mine.

The term "replacement" was used in accordance with the best American definition and usage of the term. Lindgren[2] defines it as follows: "The word metasomatism, meaning a change of body . . . is now applied to the *process of practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly differing chemical composition may grow in the body of an old mineral or mineral aggregate.*" He adds: "The secondary minerals of any metamorphic rock result from metasomatic action." In the discussion of Meso-metamorphic, and

[1] Stuckey, J. L.: Cyanite Deposits of North Carolina. ECON. GEOL., vol. 27, pp. 661–674, 1932.

[2] Lindgren, W.: Mineral Deposits, 3d ed., p. 105, 1927.

Deeper Zones, where he lists cyanite, Lindgren [3] adds:—"Minerals are formed mainly by replacement."

The cyanite in the metamorphic rocks of North Carolina is a secondary mineral and, according to the above statements, Fig. 2 in my original paper is still believed to represent replacement.

Mr. Dunn states that crystal boundaries in metamorphic rocks are not evidence of sequence, but indicate the power of a mineral to assert its crystal boundaries, and insists on "crystalloblastic order" and not "order of crystallization." It should be noted that "order of crystallization" is not referred to in my paper. His "crystalloblastic order" seems to be the same as the metasomatic or replacement order. He has stated [4]: "A small area of tourmaline rock contains irregular veins and replacement masses of sillimanite. . . . Under the microscope, the crystalloblastic order is usually tourmaline-sillimanite-muscovite, although sometimes it is sillimanite-tourmaline-muscovite."

Under the title Texture of Metasomatic Rocks, Lindgren,[5] states: "In metasomatism new minerals develop at countless points in the old rock, some growing with crystal form (metacrystic or crystalloblastic series, p. 198) while others grow into irregular grains." On page 198, under the heading Mode of Replacement, he states: "The power of crystallization of the different minerals varies greatly. . . . The following list gives the relative power of crystallization in solid rocks of some minerals, as beginning with those of strongly emphasized individuality: Rutile, tourmaline, staurolite. . . ." According to this statement, the crystalloblastic order or series in mineral deposits in metamorphic rocks is merely the metasomatic or replacement series.

In his enthusiasm for regional metamorphism, Mr. Dunn insists that the aluminous silicate deposits are all associated with highly aluminous rocks, that they occur only in rocks which already contain these minerals, and that there has simply been a re-sorting of the aluminous materials under the influence of the

[3] *Idem.*, p. 110.

[4] Dunn, J. A.: The Aluminous Refractory Materials: Kyanite, Sillimanite, and Corundum in Northern India. Geol. Surv. of India, Mem. 52, p. 208, 1929.

[5] Lindgren, W.: *Op. cit.*, p. 201.

solutions that permeated the country rock. He then adds: "Of Mr. Stuckey's conclusion of magmatic origin, I cannot but feel sceptical. . . ." The word "magmatic" does not occur in my original paper. If he means by magmatic origin to denote processes of differentiation and cooling in molten magmas, I agree. On the other hand, I am fully convinced that, without the agency of hot solutions of igneous derivation, most of the mineral deposits associated with metamorphic rocks would not exist.

Mr. Dunn nearly admits the importance of hot solutions when he states (p. 694): "This, notwithstanding that I am now approaching the opinion that highly heated waters, plutonic or inherent in the schists, are responsible for a larger part of the mineral changes during regional metamorphism than many geologists would admit, especially in mica schists."

The highly insoluble nature of alumina in cold solutions is generally recognized, as well as its wide distribution, especially in sedimentary rocks, where it is commonly considered to have been brought about by mechanical means. On the other hand, if bodies of aluminous minerals in metamorphic rocks are to be considered merely as segregations from the surrounding rock (which is hardly tenable) some means of concentration other than mechanical must be found; the most plausible is through the agency of hydrothermal solutions.

Everyone knows that many aluminous silicates, such as garnet, pyroxenes, feldspars, and micas, are deposited in many rocks from hot solutions. Even cyanite has been reported in hornblende schist by some investigators. Much alunite was probably developed by hot solutions and gases of igneous origin. Larsen[6] has recently proposed, in a convincing way, the formation of corundum and albitite by hydrothermal processes.

The aluminous mineral, pyrophyllite, was for many years considered characteristic of metamorphic rocks and metamorphic processes. Buddington[7] has stated that the pyrophyllite of the

[6] Larsen, E. S.: A Hydrothermal Origin of Corundum and Albitite Bodies. ECON. GEOL., vol. 23, pp. 398–433, 1928.

[7] Buddington, A. F.; Pyrophyllitization, Pinitization, and Silicification of Rocks around Conception Bay, Newfoundland. Jour. of Geol., vol. 24, pp. 130–152, 1916.

Avondale, Newfoundland, volcanics was formed by the metasomatic replacement of silicified rhyolite, or rhyolitic volcanics by hot water. I have shown that the pyrophyllite of the Deep River Region,[8] North Carolina, was formed by hydrothermal replacement of acid tuffs and breccias.

Analyses show that the alumina in the unaltered volcanics of the pyrophyllite areas varies from 14 to 21 per cent.; pyrophyllite contains 28.3 per cent. Buddington and I have both shown that silicification preceded the formation of pyrophyllite, reducing the alumina content of the volcanics to 8 or 9 per cent. There are no large amounts of altered or silicified tuff in sight around the pyrophyllite bodies from which alumina has been removed.

According to Clarke,[9] the average alumina content of gneisses and schists varies from 10 to 20 per cent., and in quartzite and quartz mica schist from 1.6 to 10 per cent. Cyanite contains 63.2 per cent alumina. Any appreciable amount of cyanite in these rocks will mean a marked concentration of alumina, which must be extracted from the surrounding rocks if the cyanite deposits are simple segregations.

The cyanite occurs in acid gneiss and schist, quartz-mica schist, quartzite, schistose volcanics, pegmatites, and quartz veins. It is not found regularly distributed through the schistose rocks as are the quartz, mica, and other minerals, but is concentrated in irregular bodies, many of which are almost pure cyanite. There is no evidence that the alumina content of the schistose rocks near the cyanite bodies is different from that of the same rocks a mile or two away. Moreover, every cyanite deposit examined shows evidence of igneous activity or hot solutions by the presence of pegmatites or quartz veins. The cyanite is younger than the metamorphism of the host rocks. Keith observed this thirty years ago.[10]

[8] Stuckey, J. L.: Pyrophyllite Deposits of the Deep River Region, North Carolina. ECON. GEOL., vol. 20, pp. 442–463, 1925.

[9] Clarke, F. W.: Data of Geochemistry. U. S. Geol. Surv., Bull. 695, pp. 591–628, 1920.

[10] Keith, A.: Geological Atlas of the United States, Roan Mountain Folio 151, p. 2, 1907.

An interesting deposit of cyanite, on Hager's Mountain near Roxboro, North Carolina, is in an area of medium- to fine-grained schistose acid tuff cut by many later quartz veins. Abundant cyanite has replaced both the quartz and tuff and forms cross-fiber veins in the larger quartz veins. Near the center of the mountain is a 20-foot vertical cliff disclosing four or five quartz veins, from six to eighteen inches thick, which cross the cleavage of the tuff. These veins show cores of cross-fiber cyanite veinlets from one to four inches across, and from one to four feet long. Crystalline pyrophyllite is a common filling between cyanite blades.

Taber [11] noted cyanite in the gold-bearing quartz veins of Central Virginia and concluded that it came from below as a residual material from a granite magma. Jonas [12] states that the cyanite in pegmatite dikes of central and southwestern Virginia is of igneous origin. Bayley [13] noted that near Tate, Georgia, cyanite is common in mica schist and has replaced associated quartz veins.

Pegau [14] has noted the presence of both rutile and sillimanite associated with pegmatite dikes in the Amelia-Goochland area of Virginia, and stated that both probably resulted from pegmatite juices. Anderson [15] observed andalusite and sillimanite in the pegmatites of Idaho and regarded them as primary constituents of the pegmatites. Beverly [16] found sillimanite in the graphite deposits of Los Angeles County, California, and considered that it was brought up by magmatic waters.

Mr. Dunn [17] proposes a dual origin for cyanite and associated

[11] Taber, Stephen: Geology of the Gold Belt in the James River Basin, Virginia. Va. Geol. Surv. Bull. 7, 1913.

[12] Jonas, Anna I., and Watkins, Joel H.: Kyanite in Virginia. Va. Geol. Surv. Bull. 38, p. 13, 1932.

[13] Bayley, W. S.: Geology of the Tate Quadrangle, Georgia. Ga. Geol. Surv. Bull. 43, pp. 71–73, 1928.

[14] Pegau, A. A.: Pegmatite Deposits of Virginia. Va. Geol. Surv. Bull. 33, p. 21, 1932.

[15] Anderson, A. L.: Genesis of the Silver Hill Tin Deposits. Jour. of Geol., vol. 36, p. 646, 1928.

[16] Beverly, Burt, Jr.: Graphite Deposits in Los Angeles County, California. ECON. GEOL., vol. 29, p. 355, 1934.

[17] Dunn, J. A.: *Op. cit.*, chap. 12.

aluminous minerals in India. The larger, purer deposits have been formed by the metamorphism of rather pure clays which were accumulated in Archaean time. The smaller deposits are, in part, segregations derived from impure clays. The pegmatite dikes derived their aluminous minerals from the country rock, even the mica of the mica-pegmatites came from the schists and not from the granitic source of the pegmatite solutions.

There is no information available to indicate that the cyanite of North Carolina was formed by the metamorphism of clays. The Archaean rocks of the upper Piedmont plateau and the mountain section of the state are highly siliceous and contain no lenses of pure clay, but they do show evidence of having been acted on by hot solutions.

In the lower Piedmont region, the original Algonkian rocks consisted largely of volcanics with interbedded clays and shales; all have been metamorphosed; the clays and shales were changed into slates rather than schists, and no cyanite has been found in them. It has, however, been found in the siliceous fragmental materials where igneous activity has taken place.

In the U. S. National Museum, Washington, D. C., specimen No. 97764 is commercial cyanite imported by Charles Taylor Sons Company, Cincinnati, Ohio, from Kharsawan, India. A polished section of this material, about 18 inches long by 12 inches wide, shows original banding, evidently a schistose structure produced by metamorphism. Cyanite blades with a maximum length of 6 to 8 inches cut across the structure at right angles, indicating perfect replacement. In the hand specimen, the material appears to be almost pure cyanite, but thin sections reveal that the original rock was a volcanic fragmental material which has been replaced by cyanite; shreds and fragments of volcanic glass are common.

The extended literature on pegmatites indicates that they have originated from igneous magmas and that their formation involves a long series of replacements. Their minerals have been derived from the original solutions and not from the inclosing

rocks. Landes,[18] in a recent review of the literature on pegmatites made no mention of the introduction of material into the pegmatites, but pointed out that the hydrothermal solutions often leave the pegmatites and deposit minerals in the country rock.

Mr. Dunn makes much of the fact that masses of sillimanite and corundum have been intruded by granite. There are a number of cases where granite of a later age has intruded mineral deposits of an earlier age. This in no way destroys the original source of the mineral deposits.

A careful review of all the available evidence points to the formation of the cyanite deposits of North Carolina by metasomatic replacement by hot solutions given off by the quartz veins, pegmatite dikes, and their parent magmas.

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RALEIGH, N. C.,
Jan. 22, 1935.

[18] Landes, K. K.: Origin and Classification of Pegmatites. Amer. Miner, vol. 18, pp. 33–56, and 95–103, 1933.

REVIEWS

Die Primäre Erzverteilung auf den Erzlagerstätten und ihre geologischen Ursachen[1] (The primary distribution of ore in ore deposits and its geological causes). By Dr. F. Wernicke, Geological Survey of Saxony. Pp. viii + 173, figs. 67. Wilhelm Knapp, Halle (Saale), 1933.

The author characterizes this study as a first attempt to fulfill a need pointed out by Lindgren in his report of the Committee on Processes of Ore Deposition in 1928, wherein he says the enormous array of recorded facts "calls for systematic study and a search for generalizations." A first draft of the treatise was awarded a prize at the Freiberg School of Mines in 1925. It was rewritten for a doctor-in-engineering thesis at Freiberg in 1929. As published in 1933 it represents a second complete rewriting and revision.

The work consists of four parts that differ greatly in merit and value: (I) Influence of differentiation processes in the magma on metal distribution, ore deposition, and ore distribution; (II) Influence of magmatic intrusions and extrusions on ore deposition and ore distribution; (III) Influence of tectonics on ore distribution; (IV) Influence of country rock on ore distribution.

Part I concerns magmatic differentiation and its influence on ore deposition. Wernicke does not accept the idea of a universal original gabbroic-basaltic magma but believes that the composition of the original magma depends on the depth in the lithosphere at which the magma was formed,—if in the sima zone it will be more basic, if in the sial zone it will be more acid. During a magmatic fore-phase, minerals with highest melting point crystallize out and sink to the bottom to form monomineralic partial magmas, and iron-copper-nickel sulphides separate from the silicates and collect at the bottom in molten state. During the principal stage of differentiation there is a concentration of certain metals in certain types of partial magmas, but never sufficient to form an ore

[1] Also published as a doctor-in-engineering thesis at the Freiberg School of Mines under the title: "Die primäre Erzverteilung auf den Lagerstätten in Abhängigheit von den Bildungsvorgängen und den geologischen Verhältnissen des Lagerstättengebirges." (The primary distribution of ore in deposits as determined by their origin and the geologic relations of the country rock.)

deposit. However, this concentration influences greatly the character of the subsequent ore deposition. Nevertheless it does not follow that all elements concentrated in the partial magma will be further concentrated to ore deposits. This requires the extraction and local concentrations of that metal content. In basic rocks certain ores are concentrated through sinking of early-formed crystals and unmixed sulphide melts before the main stage of mineralization is reached. This practically closes ore formation in basic magmas, because in the earliest stages of differentiation the volatile constituents are segregated into the more acid partial magmas. With continued crystallization the volatile constituents concentrate more and more the elements that do not enter into the constitution of the silicates. Finally most of the silicates crystallize, with a splitting into a basic portion and an acid portion. In this second-order differentiation Wernicke sees the birth stage of all epigenetic deposits. The dry basic magma can give rise only to the syngenetic deposits of the fore-stage of differentiation. The epigenetic deposits are the product of end-phase pneumatolytic and hydrothermal processes of intermediate and acid partial magma. The character and extent of the rock province, therefore, determines the character and extent of the genetically related metal province.

Wernicke then discusses metal concentration in basic magmas in more detail. Magmatic segregations are determined by the chemical and petrographic character of the mother rock. Very small changes in the mother rock give rise to marked changes in the character of the ore concentration. The processes in basic magmas are crystallization differentiation and unmixing. Crystallization differentiation gives rise to deposits of platinum, chromite, ilmenite, and magnetite. Platinum deposits occur in rocks very low in silica (generally 40 per cent. SiO_2 or less) and high in MgO and FeO. Chromite deposits occur in rocks a little higher in silica (43–45 per cent. SiO_2) and high in MgO. Ilmenite deposits occur in gabbros still higher in silica (55 per cent. SiO_2). With increasing MgO ilmenite gives way to chromite, with increasing SiO_2 it gives way to magnetite, and with increasing SiO_2 content in the differentiate, magnetite becomes less and less syngenetic and more and more the product of mineralizers, and grades over to epigenetic magnetite that may be deposited beyond the magma itself. First-order differentiation enriches the gabbro magma in sulphides. Second-order differentiation results in unmixing of the sulphides from the silicate melt. If differentiation goes on undisturbed, the sulphides accumulate in layers at the bottom in less concentrated form. If injected as partial magmas, they occur at the peripheral cooling surfaces in smaller, more concentrated ore bodies. The sulphide deposits are characteristic of norite magmas. The injected partial magmas may be more or less diluted with volatiles so that their intrusion may

be not solely mechanical but due also to "magmatic activity" and grade over into intrusive sulphide deposits, forming a transition type analogous to the magnetite deposits.

Second-order differentiation in intermediate and acid rocks also manifests characteristic metal associations within narrow ranges of composition of the partial magmas. These restrictions are often obscured and not recognized because of the epigenetic nature of the deposits which makes it difficult to recognize the immediate source of the mineralizers; and when recognized, the ultimate source of the partial magma may not be recognizable. Thus, either a diorite or augite monzonite magma may yield a biotite-quartz monzonite. The metallization resulting from the differentiation of the biotite-quartz monzonite will depend on which magma it was derived from. An intermediate magma near basic composition is unfavorable for ore deposition because the syngenetic metals of the fore-stage have already been separated from it and the concentration of mineralizers in it is inadequate to extract metals for epigenetic mineralization. Dilute pegmatitic and aplitic melts are the mother-liquors of a completed differentiation cycle. They are often rich enough to constitute ore deposits. Generally ore deposits form only in a still later stage, when most of the silicates have been deposited and the rest-solutions have undergone a final concentrating through the boiling off of excess water. Extreme acid differentiates consist of: (*a*) eruptive quartz veins, pegmatite and aplite dikes, which when of granitic origin contain syngenetic deposits of tin, tungsten, and arsenic and when of quartz monzonite and diorite origin contain syngenetic deposits of copper-iron sulphides and molybdenite; (*b*) aplitic and very rich granitic stocks with epigenetic pneumatohydatogenic deposits of tin, tungsten, and molybdenite. Normal granite batholiths of first-order differentiation with diaschistic dikes yield hydrothermal deposits that include: (*a*) a gold-free branch characterized by hydrothermal lead, zinc and silver and contact-metamorphic magnetite, and (*b*) a gold-bearing branch which is derived from a granodiorite root. Intermediate differentiates of the first order belong to the diorite family and yield deposits in which gold, silver, and copper predominate and zinc and lead are subordinate. The less acid the differentiate, the higher the ratio of copper to lead and zinc.

Some of the relationships pointed out by Wernicke and some of his generalizations are well established and have been repeatedly recognized in the literature of ore deposits; others are interesting and daring but would not be conceded without question; still others would be challenged by most economic geologists. Recent literature on chromite, ilmenite, and magnetite deposits does not corroborate the simple syngenetic origin ascribed to these deposits by Wernicke. In the case of the sulphide deposits the literature is even more at variance with his ideas. Throughout

the work the postulated relations are illustrated by abundant references to actual ore deposits. In many cases, even though the conclusion may be acceptable, the illustration would not be accepted as evidence of its validity. Thus, the Rio Tinto deposits are cited as examples of intruded sulphide deposits. It is apparent over and over again that Wernicke has assimilated more literature than he has been able to digest properly, and that he does not thoroughly understand the geologic background of many of the examples he cites. Irrespective of the extent to which one may disagree with the author in this first part of his work, the presentation is worthy of thoughtful reading.

Part II deals primarily with the influence of magmatic processes on zoning and paragenesis. The depth of the exhalation center determines the character of the ore distribution. The equalization of temperature and pressure at ultrabyssal depths is unfavorable to the concentration of mineralizers. Well defined channels are lacking and the exhalations must rise by diffusion and react with favorable country rock. The process is related to that of contact-pneumatolytic deposits. Uniform mineralization persists over a great vertical range. The younger the mineralization, the higher lay the magma from which the mineralizers were derived, i.e., the higher the exhalation center. Similarly the vertical range of the ore zones becomes smaller, until in the case of extrusives telescoping results. Similarly, also, the horizontal extent of the mineralized area becomes more and more restricted. The horizontal and vertical persistence of zones depends also on the size and shape of the intrusive. Further, the more differentiated the lower part of the batholith and the more irregular the upper surface, the greater the concentration of mineralization in the favorable loci which are the high points of the intrusion. The pressure gradient exerts only a modifying effect on the temperature gradient. Zoning may be modified under two conditions: (1) the character of the exhalations remains constant, and (2) the character of the exhalations undergoes progressive change. In the first case, if the isotherms are moving inward, i.e., if mineralization occurs under cooling conditions, upper zones are superimposed upon and replace the lower zones. If the isotherms are moving outward, i.e., under conditions of magmatic rejuvenation, lower zones are superimposed upon and replace upper zones. In the second case, a similar superposition of zones may result. Wernicke contends it is impossible to set up a single or linear zonal sequence, as is attempted by Spurr and Emmons, because zoning is dependent on the preceding differentiation processes and the character of the exhalations and hence on the magma type from which the exhalations are derived. Though roughly the same, the zoning of different magma types is distinctive. The same remarks apply to paragenetic sequences.

Wernicke believes there is an optimum depth of maximum metal deposition which diminishes both downward and upward, the vertical range of which varies greatly, and the boundaries of which may be relatively abrupt or transitional. Hence workable ore grades downward into lean or barren "vein roots" and upward into lean or barren gangue. Examples of this phenomenon and of the distribution of the metals within the optimum zone are cited for a number of types of ore deposits. Hasty and inadequate utilization of the literature is in evidence here also. The presentation of the silver-tin district of Bolivia is based solely on an abstract of the paper by W. M. Davy in the Zeitschrift für praktische Geologie (the name is erroneously written Daly, and so copied by Wernicke). As an example of primary difference in depth in copper-iron sulphide deposits, the United Verde mine is described as showing a decrease in copper content from 24 to 3.2 per cent. between ground-water level and a depth of 530 meters. The statements in the original literature, however, are clearly concerning secondary enrichment in the United Verde Extension mine!

The entire process of ore deposition is divided into two distinct periods: (1) mineralization and (2) metallization. The most important phase of mineralization precedes metallization, and represents a forestage during which excess solutions are distilled off, and the metals are further concentrated in the rest-magma. It causes widespread alteration of the country rock. The following metallization is much more restricted in extent. These processes are illustrated by the alunitization and gold deposition, respectively, at Goldfield. A second phase of mineralization often follows metallization and is represented by the barren gangue veins which often surround the productive area.

The third section of part II treats of ore shoots. Local variations in magmatic exhalations, local tectonic features, and physical and chemical character of the wall rock, are influences that determine the occurrence of ore shoots. Ore shoots are most abundant in the zone of optimum metallization. In easily penetrated rocks they tend to pipe-like shapes, in more resistant rocks they are more tabular. The character of an ore deposit depends greatly on the relation between solution and deposition. If removal greatly exceeds addition, collapse breccias result. In replacement deposits removal and addition nearly balance. In veins addition exceeds removal, and space may be made mechanically by the force of crystallization.

Part II presents some useful generalizations and some amendments and supplements to current understanding of zoning and paragenesis. It gives the student of ore deposition ideas to think about.

Part III discusses the influence on ore distribution of regional pre-magmatic and co-magmatic tectonic openings and of local pre-magmatic

and post-magmatic disturbances. In depth only shear zones are available as loci of ore deposition, whereas close to the surface fracturing tends to express itself as complex stockworks. In undisturbed regions there is no mineralization because no space has been prepared; on the other hand, ore deposition occurs only in a small fraction of the whole space tectonically formed. Metallization is repeatedly associated with anticlines formed by regional forces just prior to or during magmatic intrusion. Cross tears along shear zones are more favorable loci than the shear zones themselves. Steeply dipping fractures less filled with friction products are more favorable than flatter overthrust surfaces. Frequently zones of pressure disturbance are later opened by tension.

Tectonic disturbance alone does not result in ore deposition; the fractures must tap a magmatic exhalation center. Hence, tectonic disturbances connected with igneous intrusion are especially conducive to ore deposition. Fractures caused by the magma in its upward surgence and the crustal adjustments accompanying its subsequent cooling are the loci of dikes and veins. The repeated reopening of veins shows that equilibrium is reached very gradually and slowly.

The discussion of the local effect of disturbances is largely a description of the phenomena where younger mineralized disturbances meet pre-magmatic disturbances, of the effect of post-mineral disturbances on ore bodies, and of the variations in ore bodies determined by variations in the structural feature in which mineralization occurred.

Even less philosophical than Part III is Part IV, which deals with the effect of the physical and chemical properties of the wall rock on ore deposition. Physical factors considered are strength, grain size, and permeability. Extremely soft and extremely brittle rocks are least favorable for well developed fractures. Adsorption in clayey rocks may compensate in part their unfavorableness to cavity formation. Selective adsorption affects the relative distribution of metals in vein walls and in the cavity. If the matrix of a rock is soluble, the fore-mineralization may greatly increase its permeability for the metallizing solutions. Under chemical influences are considered the behavior of carbonate rocks, the effect of less resistant constituents of silicate rocks, and the rôle of chemically active accessory constituents of rocks. Easily and completely soluble rocks like limestone are favorable to ore deposition and determine the shapes of ore bodies. Silicate rocks yield impregnation zones rather than complete replacements. Basic rocks are more active chemically than acid, and ferrous iron minerals are especially effective precipitants. Precipitation is also caused by the reducing action of organic substances, by hydrogen sulphide emitted by sulphides, and by potential differences between minerals. The electrochemical effects of older sulphides are

especially emphasized. In general the influence of the country rock increases as the activity of the mineralizing solutions decreases.

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Kyanite and Vermiculite Deposits in Georgia. By L. M. PRINDLE ET AL. Pp. 50, figs. 4, pls. 11. Geol. Survey of Georgia, Bull. 46. Atlanta, 1935.

Kyanite has long been known to exist in widely scattered localities in Georgia, but it is only within the past year that a systematic study of the geographical distribution of its occurrences has been undertaken. The report now presented describes many of the localities at which kyanite has been found and a few at which vermiculite is common.

The kyanite, as had already been ascertained by earlier geologists, exists with staurolite, tourmaline and other metamorphic minerals in mica schists and also in quartz veins. It is now recognized as existing also in placer deposits, some of which are comparatively rich. The most positive result of the field study was the discovery of a belt of kyanite-mica schists 30 miles long in Habersham and Rabun counties and of placers associated with them that carry in some places 40 lbs. of comparatively pure kyanite to the cubic foot of gravel. At several places the weathered schists and the placers were being worked during the summer of 1934. Schists containing kyanite in large quantities, and placers, mainly of quartz and kyanite, are described from other areas also, but very little new information is added as to the mode of occurrence of the mineral or its origin. Prindle concludes that the placer deposits will furnish noteworthy supplies of kyanite for a few years, but that the development of a stable industry must depend for the most part upon the kyanite schists. In the thought of the reviewer it might be more accurate to say it will depend upon the discovery of an area where the schists are cut by many quartz-kyanite veins.

Only a few pages of the report are devoted to vermiculite. This mineral is stated to have been found with basic rocks near Atlanta, and in a few other places, but the only known deposits of sufficient purity to be of possible commercial value are in Towns and Rabun counties, and even at these places, which are described, the prospects are not very promising.

W. S. BAYLEY.

Über Entmischungen im System Cu-Fe-S und ihre Bedeutung als "geologische Thermometer." By HERMANN BORCHERT. Chemie der Erde, vol. 9, pp. 145–172, 1934. Figs. 32, pls. 2.

This paper contains a wealth of new data, principally experimental, on the relations of the minerals composed of copper, iron and sulphur. Im-

portant modifications and amplifications of previous papers appear necessary if most of the ideas set forth are finally accepted. In addition to bornite, chalcopyrite, cubanite, and pyrrhotite, Borchert recognizes two minerals which are not usually mentioned; that is, valleriit and chalcopyrrhotite.

Cubanite has recently been shown by Ramdohr to have two forms designated as Cubanite I, the usual form stable below 235°, and Cubanite II, which forms from I at 235°. The higher-temperature form appears isotropic and is somewhat darker and of a browner color than the normal form. Cubanite II is not uniform but contains a lamellar intergrowth which enlarges at 330° and is said to be chalcopyrrhotite ($CuS.Fe_4S_5$), which develops from cubanite at 235°. It has a pale yellow-green color when compared with pyrrhotite on a polished surface. With chalcopyrite it appears light brown. Pyrrhotite slowly dissolves in chalcopyrite above 300°, forming by diffusion an intergrowth which is essentially like that formed by unmixing. If a solid solution of pyrrhotite in chalcopyrite is cooled from a temperature of 600°, unmixing of chalcopyrrhotite begins at about 450° and ends at 300°.

Valleriit occurring as inclusions in chalcopyrite is stable only to 225°. At this temperature CuS diffuses into chalcopyrite and pyrrhotite remains.

Chalcopyrrhotite is stable between 255° and 450°–550°. Below 255°, by very slow cooling, it will separate into pyrrhotite, cubanite or valleriit and chalcopyrite. Above 550°, it forms a solid solution with chalcopyrite or pyrrhotite.

Above the solution curve three solid solutions are known: (1) Chalcopyrite with chalcopyrrhotite in solution; (2) chalcopyrrhotite with pyrrhotite or chalcopyrite in solution; (3) pyrrhotite with chalcopyrrhotite in solution.

Chalcopyrrhotite decomposes into chalcopyrite and pyrrhotite by very slow cooling between 255° and 235°, and by very slow cooling below 235° separates into cubanite and pyrrhotite or into chalcopyrite, cubanite and pyrrhotite. A diagram of the stability in the system Cu-Fe-S is shown as Figure 8.

Oxidation is said to form chalcopyrrhotite at the expense of pyrrhotite, chalcopyrite at the expense of chalcopyrrhotite, and bornite at the expense of chalcopyrite, apparently through the combination of iron as oxide and sulphur.

As a result of the experimental work, the temperature of formation of several deposits is discussed. The deposits at Kaveltorp, Sweden, for example, are judged to have formed near 250°. The last stages of rearrangement at Sudbury are believed to have occurred between 235° and 255°.

G. M. SCHWARTZ.

Getting Acquainted with Minerals. By G. L. ENGLISH. Pp. 324, figs. 258. Mineralogical Publishing Co., Rochester, N. Y., 1934. Price, $2.50.

The author states: "The aim of this book is to introduce the charming science of mineralogy in the simplest and most interesting manner possible, without sacrificing scientific accuracy." This aim has been achieved. If one wishes to learn something about mineralogy, no more interesting book can be found; if he wishes to learn mineralogy, he will turn elsewhere.

Part I, "about minerals in general," deals with their properties and interesting features; Part II, with descriptions of selected minerals; Part III, with descriptions of rocks. An appendix on mineral identification and pronouncing vocabulary are included. Optics are omitted, and the book stresses physical properties and simple tests The minerals are classified according to their important elements arranged alphabetically, or as rock-making minerals, and are excellently illustrated.

The Great Design: Order and Progress in Nature. Edited by FRANCES MASON. Pp. 324. Macmillan Co., New York, 1934. Price, $2.50.

A series of essays by fourteen prominent scientists, designed to awaken curiosity and interest in nature and to show that the ordered harmony of nature points to a Directing Mind.

The subjects include astronomy, geology, evolution, botany, and philosophy. Among the authors are: Sir J. A. Thomson, Bailey Willis, R. G. Aitken, J. A. Crowther, E. W. McBride, Sir Oliver Lodge, and Hans Driesch. Selected bibliographies are appended to each chapter for those who wish to delve further.

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DAVID GALLAGHER.

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History and Work of Geological Surveys and Industrial Development in Alabama. W. B. JONES. Pp. 116, pls. 7. Alabama Geol. Surv., Bull. 42. University, 1935. Contains also bibliography of Alabama geology, by R. M. Harper, with 485 entries.

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Bário. O. H. LEONARDOS. Pp. 20. Serv. de Fomento da Prod. Min. do Brasil, Avulso 2. Rio de Janeiro, 1934.

Carvão Mineral do Norte do Paraná. G. DEP. TEIXEIRA AND E. B. DUTRA. Pp. 52, pls. 10, figs. 7. Serv. de Fomento da Prod. Min. do Brasil, Bol. 4. Rio de Janeiro, 1934.

El Yeso en Lima. G. D. ZEVALLOS. Pp. 179, figs. 44. Cuerpo de Ingenieros de Minas del Peru, Bol. 110. Lima, 1934.

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Floods and Accelerated Erosion in Northern Utah. R. W. BAILEY, C. L. FORSLING, AND R. J. BECRAFT. Pp. 21, figs. 8. U. S. Dept. Agriculture, Misc. Pub. 196, 1934.

Gas-, Coke-, and Byproduct-Making Properties of American Coals and Their Determination. A. C. FIELDNER AND J. D. DAVIS. Pp. 164, figs. 28, tables 32. U. S. Bur. Mines, Monog. 5. Printed by American Gas Assoc., N. Y. 1934.

On Kaersutite from Dôgo, Oki Islands, Japan, and Its Magmatic Alteration and Resorption. T. TOMITA. Pp. 38, figs. 10, pls. 3. Jour. Shanghai Sci. Inst., Sect. II, Vol. I. Shanghai, 1934.

Geology of Central Mewar. B. C. GUPTA. Pp. 183, figs. 2, pls. 10. India Geol. Surv., Mem. Vol. LXV, Pt. 2. Calcutta, 1934. Rs. 4–12 or 8/. General geologic description, colored map.

The Baluchistan Earthquakes of August 25th and 27th, 1931. W. D. WEST. Pp. 89, figs. 1, pls. 8. India Geol. Surv., Mem. Vol. LXVII, Pt. 1. Calcutta, 1934. Rs. 3 or 5/3.

McCoy Mining District and Gold Veins in Horse Canyon, Lander County, Nevada. F. C. SCHRADER. Pp. 13, figs. 2. U. S. Geol. Surv., Circ. 10. Washington, 1934.

Geologische Charakterbilder, Pt. 40: Die Salsen von Beciu-Berca (Rumania). K. KREJCI-GRAF. Pp. 22, pls. 8, quarto. Gebrüder Borntraeger. Berlin, 1935. 11.50 M. The 40th part of a series of excellent photographs illustrating geological phenomena; it pictures mud eruptions along the axis of an anticline in Buzen, Rumania; accompanied by text describing the mud flows and mud volcanoes.

SCIENTIFIC NOTES AND NEWS

E. O. Teale has been appointed mining consultant to the Tanganyika Government.

F. R. Wade has been made Director of the Geological Survey of Tanganyika.

A. L. Hall, until recently the assistant director of the Geological Survey, Union of South Africa, has been elected a Fellow of the Royal Society.

R. B. Young, recently retired from the chair of Geology at the University of the Witwatersrand, has been awarded the Draper Memorial medal.

A. W. Fahrenwald has been appointed Dean of the University of Idaho College of Mines, to succeed John W. Finch, now Director of the U. S. Bureau of Mines.

G. Carleton Jones is president of the Geological Society of South Africa.

J. J. Beeson, geologist for Park City Consolidated Mines, is president of the Silver-Lead Syndicate, with offices in Salt Lake City, Utah.

Clinton Bernard, consulting engineer, General Development Company, New York, has recently been spending several weeks in Colombia.

R. M. Overbeck, of the International Mining Corporation, has been spending nine months in Mexico at one of the corporation mines, and has now returned to New York.

Russell V. Johnson, of Calgary, Alberta, has been elected vice-president of the Alberta Society of Petroleum Geologists for 1935.

Gerald G. Dobbs has been appointed assistant general manager of Gold Coast Selection Trust, Africa.

E. N. Pennebaker, of Consolidated Coppermines, Kimberly, Nevada, is making an examination at Bisbee, Arizona, for the Phelps-Dodge Corporation.

A. I. Levorsen is president of the American association of Petroleum Geologists for 1935, and L. C. Snider is editor for the Association.

Hans Lundberg announces that the firm of Hans Lundberg, Ltd., will hereafter have no connection with Swedish American Prospecting Corporation, but will use its own methods and patents.

Ernest F. Burchard, of the United States Geological Survey, has been awarded the honorary degree of doctor of science by the University of Alabama.

The Third Annual Petroleum Conference of Illinois-Indiana was held on Saturday, June 1st, at the Crawford County Country Club, Robinson, Ill., sponsored by the Petroleum Association, the Geological Survey, and the State Division of Geology, Department of Conservation.

The 17th International Geologic Congress (first circular) announces the session to be held in Russia in July and August, 1937. President, I. M. Goubkin; Secretary, A. E. Fersman, Moscow 4, Kotelnicheskaya Naberezhnaya 17. Topics: (1) Petroleum resources of the world; (2) Geology of coal fields; (3) Pre-Cambrian and Mineral Deposits; (4) Permian System; (5) Correlation of tectonics, magmas, and ore deposits; (6) Tectonic and geochemical problems of Asia; (7) Deposits of rare elements; (8) Geophysical methods; (9) History of geological knowledge. Pre-Congress excursions: *A-1*—Northern, 15 days. Pre-Cambrian, Igneous and minerals. *A-2*—Urals, 20–22 days. Tectonics, stratigraphy, ores. *A-3*—Southern, 20 days. Pre-Cambrian, iron ores, coal, salt, stratigraphy. *A-4*—Volga, 20 days. Mesozoic, engineering geology. *A-5*—Caucasus, 26 days. Stratigraphy, tectonics, volcanism, manganese and iron. Post-Congress excursions: *C-1*—Petroleum and stratigraphy, 50 days. *C-2*—Central Asia, 50 days. Stratigraphy, tectonics, volcanism, mining. *C-3*—Transcontinental, 50 days. Various. *C-4*—Turkestan, Siberia, 40 days. General and mining.

Harry Cyril Boydell, geologist and consulting mining engineer of Toronto, Canada, died at Chester, Nova Scotia, April 16, aged 56.

Max Roesler, consulting geologist, Cornwall-on-Hudson, N. Y., died suddenly of pneumonia in the New Haven hospital, on May 26.

Leopold Reinecke, formerly with the Canadian Geological Survey, and since 1923 a consulting geologist in Johannesburg, South Africa, died April 17 on board ship en route to Africa after a trip to London for treatment.

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